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HYDROGEN AND OXYGEN SENSOR DEVELOPMENT

Contract No. NAS 10-1255 Mod 25

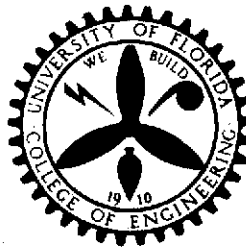
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HYDROGEN AND OXYGEN SENSOR DEVELOPMENT

Contract No. NAS 10-1255 Mod 25

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Launch Instrumentation Systems Division

W.R. Helms

Technical Representative

Kennedy Space Center, Florida

Prepared by

Dr. E. A. Farber

Dr. J. Mahig

Dr. H.R.A. Schaeper

University of Florida

Florida Engineering and Industrial
Experiment Station

Department of Mechanical Engineering
Gainesville, Florida

HYDROGEN AND OXYGEN SENSORS DEVELOPMENT

ABSTRACT

The task described in this report was to develop a reliable and low cost gas sensor which would be capable of instantaneously detecting H_2 in N_2 , H_2 in air, and O_2 in N_2 . The major portion of the time was spent in developing a sensor which would instantaneously detect H_2 to ± 50 ppm even in the presence of trace amounts of other gases.

To be able to do this is of great importance in the space program where large amounts of oxygen and hydrogen are handled in connection with the large and complex rockets, the space shuttle and in and around the support facilities. Leaks must be detected quickly to prevent disastrous explosions and fires.

The device or sensor developed for this purpose through this investigation proved to be small, inexpensive, light, accurate and reliable. These sensors can be installed in and around space vehicles and facilities and are integrable in a warning system, utilizing either read-out or computer scanning and analyzing system. Only the sensor itself was the subject of this study and the complete detection system, incorporating these sensors, must be developed for particular applications to have the required characteristics and must then be analyzed with respect to a number of criteria one of them being economics.

The above approach, utilizing the principles of fluidics resulted from a thorough survey of the present state of the art of gas detection devices. It was determined which kind of sensors was ever proposed, which were used and how they performed in detecting hydrogen and which had the greatest potential for providing the ideal hydrogen detector. The study was conducted by surveying published works, company reports,

and by direct inquiry at several companies and laboratories which had been engaged in the design of such sensors.

After examining the properties inherent in each of the proposed devices, the fluidic oscillators seemed to have the greatest potential for satisfying the requirements set down for this study involving hydrogen and oxygen powered craft and their support facilities.

With this decision made a brief introduction to fluidics and the analysis of fluidic circuits for each of two types of fluidic oscillators is presented. It covers the determination of resistance, inductance and capacitance of fluidic circuits and characteristics of systems containing them. A description is given of the two basic types of fluidic oscillators developed at the University of Florida as hydrogen detectors.

They are feedback oscillators, designated as F and S series, and edgetone oscillators, designated as M series.

A. Feedback Oscillators (F & S): The theory of operation is presented for this type of oscillator and the changes in design and how they effect the performance. The F series oscillators encompass the pilot designs allowing easy changes and variation of the critical parameters to study the effects and to give the desired results. The S series being the final product meeting the required specifications. Results of calculations are compared with experimental results. Figures present the various stages of the development and performance curves give the variation of frequency of oscillation with concentration of the gas under investigation.

B. Edgetone Oscillators (M): Again the theory of operation of this type fluidic oscillator is presented and calculated results compared with results obtained during experimentation. Performance

curves are presented.

Since the fluidic oscillators are to be used as "sniffers" a vacuum must be provided to allow the gas mixture to be analyzed to be drawn through the device. A vacuum line may directly be provided for operation of the detector. If this is not available methods of providing this vacuum from other sources is discussed such as water ejectors if water lines are available, or gas ejectors if air or gases such as Nitrogen are available under pressure. The ejector design and a number of the ejectors are presented. If electricity is available and does not provide a hazardous condition either sophisticated vacuum pumps or simple aquarium types may be used.

The experimental procedures used to provide the performance characteristics for the various oscillators are discussed describing the equipment with help of schematics and photographs where applicable. The resulting performance is given in graphical form.

In some cases both hydrogen and helium may be present and since both of them effect gas sensors similarly, a method must be found to determine the concentration of each.

The methods uncovered can be grouped into the following four broad categories:

- Pure metal response
- Variation in heat conductivity
- Reduction methods
- Exotic processes

From the above it was decided for the present to use a copper oxide reduction process as this process was demonstrated to be capable of separation so that the concentrations of hydrogen and helium respectively

could be determined in a gas mixture with air or nitrogen. The exact method, calculations and data are presented.

Since under severe operational conditions the oscillators may be subjected to variations in temperature, pressure, and wind gusts, these conditions were simulated in the laboratory and then some oscillators were used to monitor the hydrogen clouds resulting from the auto-ignition field tests at the Kennedy Space Center and the results are shown.

It is believed that the work presented in this report will materially help the Space Program and provide new information with regard to the use of fluidic oscillators in the detection of hydrogen leaks in space vehicles, storage and transfer areas before these leaks result in explosions and fires.

ACKNOWLEDGEMENTS

It is with sincere appreciation that the authors thank the graduate assistants who have worked on this project and who have given assistance in the experimentation, computations, and preparation of graphs. Further thanks are given to Mr. W. R. Helms, the NASA technical representative, who contributed greatly through administrative action to the execution of this contract.

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Definitions of Symbols

Listed in order of appearance

ρ	Density
h	Enthalpy
p	Pressure
t	Time
u, v, w	Velocities in 3 dimensions
k	Thermal Conductivity
x, y, z	Coordinates
γ	Bodyforce per unit mass
μ	Viscosity
V	Volume
T	Temperature
\vec{n}	Unit normal Vector
A	Area
P_m	Mechanical Power
ϵ	Mechanical Potential
R	Radius
λ	Wave Length
$ c $	Wave Propagation Velocity
ω	Angular frequency
f, k	Specific Heat Ratio
S	Entropy
β	Constant
a	Velocity of Sound
τ	Shear Stress
C_f	Coefficient

L_e	Inertance per unit length
R_e	Resistance per unit length
C_e	Capacitance per unit length
m	Mass
i	$\sqrt{-1}$
w	Weight flow rate
C_d	Drag Coefficient
g	Gravitational Acceleration
R_g	Gas Constant
L	Length
D	Diameter (Hydraulic)
P	Wetted Perimeter
C_v	Specific heat, constant volume
C_p	Specific Heat, constant pressure
M	Mach number
T_L	Throat, nozzle
p_o	Stagnation Pressure
J	Mechanical Equivalent
$*$	Sonic Velocity Reference Point
v_j	Nozzle jet velocity
v_{FB}	Feedback Loop Velocity
Re	Reynolds number
F	Friction Coefficients

CURRENT SENSOR TECHNOLOGY

Introduction

Many of our space vehicles including the Saturn V series as well as the proposed Space Shuttle utilize hydrogen as fuel and oxygen as oxidizer and either helium or nitrogen as part of the purge system. Because of the danger of explosion and fire from a hydrogen leak, it is desirable if not necessary to assess not only if hydrogen is present but the level of concentration of hydrogen. Therefore, the application of a detector would not only give added protection to the vehicle but also to the storage and transfer areas.

At present the means for detecting a hydrogen leak is through the use of catalytic sensors, gas chromatographs and mass spectrometers. All these devices have serious limitations. The catalytic sensors are essentially warning devices and the other two methods require time to collect, transport, and then analyze a sample of gas. Through computer coordinated sequence changes the procedure for sampling which at present takes several minutes can be altered so as to sample gas from the suspected area every few seconds. However, even under these circumstances, the information obtained is not the current status but that of the time when the sample was taken. Clearly, a device is needed which will give an instantaneous determination of the concentration of the hydrogen in any one of the areas monitored.

Another device used to detect hydrogen is the Thermistor, it is extensively applied in storage areas and at critical points along hydrogen lines such as at valve locations. These devices have not proven themselves satisfactory even in this application because of their

non-linear response to hydrogen concentrations. Furthermore, there have been occasions when the detectors have responded to He instead of H_2 indicating a hazardous condition when there was none.

Early in this study program it was recommended that the basic characteristics of fluidics be applied to this problem since a detector based upon these principles, e.g. a fluidic oscillator, seemed to have the greatest potential of overcoming the weaknesses of the present systems, namely that it could detect low concentrations of hydrogen almost instantaneously even in the presence of helium.

The fluidic sensor, it was felt, would when the development program is completed prove to be a reliable, small, light, inexpensive and sensitive detector. Further, this sensor would be able to reach almost any region since it is small and lightweight and its design would allow placement in remote locations where it could instantaneously sense any changes in hydrogen concentration.

In spite of the apparent advantage of the fluidic gas sensor it was considered useful to consider available hydrogen detectors which are commercially available to determine where additional development could produce significant improvements in capability.

Hydrogen, Helium Detectors

At present, there are several proposed as well as commercially available sensors for detecting hydrogen mentioned in the literature. They are listed in Table I where it should be noted that the following systems:

- A. Fuel Cells
- B. Polarographics
- C. Kryptonate

- D. Palladium Tube
- E. Sonic Velocity Gas Analyzers
- F. Fluidic Oscillators

were all at one time in some active stage of development, though they do not seem as far as we can determine, under active development now. The above, except for item F which will be treated in detail later, do not appear to have great potential, mainly because of the complexity, high maintenance requirements and uncertainties of prototype performance. Only five types of sensors are commercially available which can detect hydrogen. They are:

- A. Mass Spectrograph
- B. Gas Chromatograph
- C. Catalytic Combustion Devices
- D. Thermal Conductivity Devices
- E. Optical Interferometer

Table I PROPOSED AND COMMERCIAL HYDROGEN SENSORS

CONCEPT	COMPLIANCE REQUIREMENTS	LEVEL OF SIMPLICITY	ANTICIPATED MAINTENANCE
Catalytic Combustion (Commercial Equipment)	Response time is less than 2 seconds (mildly affected by the presence of helium).	Very simple. (Its main sensing element is a Wheatstone Bridge. It requires no reference chamber and no sample drawing).	Little Required
Thermal Conductivity (Commercial Equipment) Note: This would be a very good method of detection if the test gas could be passed through a helium absorber prior to testing.	Response time is approximately 1 second (greatly influenced by the presence of helium).	Simple	Little Required
Fuel Cell (Developmental State)	Response time is approximately 2 seconds. (The fuel cell showed no response to a propane atmosphere. The effects of other hydrogen carbons are unknown).	Average complexity (The fuel cell has very simple electrical circuitry).	Average (Periodic oxidizer replacement would be required. It may also be necessary to provide a means to keep the gas permeable membrane moist when no hydrogen is present in the test atmosphere.)
Optical Interferometer (Commercial Equipment)	It has a response time of 3 seconds (it is affected by the presence of helium)	Complex. (This is a very complex piece of equipment. It requires a sample drawing system, a separate reference chamber and complicated electrical circuitry. In addition, it is hard to adjust for proper operation).	Average. (Frequent calibration of the adjustment controls would be required).
Polarographic (development stage)	It has a response time of 3 seconds. (it is very selective to hydrogen if properly adjusted)	Complex (This detector would be difficult to assemble and disassemble)	Average. (Frequent addition of electrolyte may be necessary. This would require disassembling the detector).

TABLE I, Continued

18

Kryptonate (developmental stage)	It has a response time of 20 seconds. (This detector has a potential response of approximately 1 second if it is operated in an air atmosphere. At present state of development it appears to have good selectivity to hydrogen).	Average Complexity	Large amount of maintenance required (frequent kryptonate replacement would probably be required).
Palladium Tube	It had a 60 second response time and a projected maximum sensitivity of 2 ppm hydrogen in air.	Complex	Average
Sonic Wave Analyzer	It has a response time of less than one second (affected by presence of H ₂).	Average Complexity	Average
Fluidic Oscillator	It has a response time of less than one second	Simple	Little required.

Brief Description of Operational Sensors.

See Table II which is compiled from the Boeing Report (2), the opinions of which do not necessarily reflect the opinions of these investigators.

The Optical Interferometer is a very complex and delicate piece of equipment requiring frequent complicated calibration and adjustments.

The Mass Spectrometer is at present used at the Kennedy Space Center. Although it is both a sensitive and discriminatory instrument, it does not give the desired performance because the speed of response is low. This is partially so because all gas samples must be brought to a centralized location required to house the complex instrument. This instrument is further dependent upon 3 power sources, LN_2 , and cooling water.

The Gas Chromatograph, although having a sensitivity similar to that of the mass spectrometer, is much slower in analyzing a given specimen and requires more time for calibration and adjustment. The time to sample and purge, for example, is four minutes, which seriously degrades the scanning rate.

The Catalytic Combustion Device is at present used for hydrogen detection at remote locations throughout the Kennedy Space Center. These sensors are primarily used as level detectors as their non-linear characteristics would seem to prohibit their use as a gage. Some observers feel that its potential for erratic behavior makes this sensor not as reliable as is desired, and thus, the search should be continued for a more reliable substitute. It cannot in its present form distinguish between hydrogen and helium.

Thermal Conductivity Detectors would appear to provide a very accurate and satisfactory sensor. They operate on the principle that

the thermal conductivity of hydrogen is about eight times that of air. This ratio remains constant over a relatively large temperature range. However, since the thermal conductivity of He is within 10% of that of H₂ the sensor can become confused in the presence of He. It is not used at the Kennedy Space Center.

Thermal Conductivity at 32°F

Air	0.0129
H ₂	0.0895
He	0.0802

A chart is provided in Table II which summarizes this discussion in a convenient form.

Potentially Improved Detection Sensors

Since the present state of the art in gas detection is not satisfactory our group suggested a break with past practices and initiated new and different ideas to solve the problem. Among them are the use of fluidic (oscillators), thermionic, and direct energy conversion devices.

Although a solution which satisfies all the real requirements outlined earlier may prove to be difficult to obtain, fluidic oscillators, thermionic converters and other DEC (direct energy conversion) devices, etc., show the greatest promise.

Although all the sensors discussed above were considered, the fluidic sensor appeared to provide the greatest potential, and was recommended for development under this contract.

Further investigations and literature surveys and personal contacts covering fluidic devices showed that some work had been done using fluidic oscillators as sensors for determining gas concentrations

TABLE II - SUMMARY OF HYDROGEN DETECTION METHODS

PHYSICAL PROPERTY OF HYDROGEN USED	METHOD OF DETECTION	RANGE OF OPERATION	ENVIRONMENTAL MIXTURES LIMITATIONS
Density	Mass Spectrometer measures the mass-to-charge ratio of ionized molecules of the sample gas.	0.01 ppm - 10,000 ppm with 5% accuracy and response time less than 1 sec.	None
Propagation Speed of Light	Optical Interferometer compares the speed of light through the sample gas to the speed of light through a reference gas.	0.1 - 2% H ₂ in air with accuracy of \pm 0.1%	Useful for binary mixture only.
Propagation Velocity of Sound	Acoustic measures the velocity of sound in sample gas.	No independent system of this type exists. A gas chromatograph with a differential analyzer using this principle can detect 1 part per million hydrogen in air	Useful only in binary mixtures (i.e., H ₂ + He, etc.)
Thermal Conductivity	Gas Thermal Conductivity measures sample gas conductivity by measuring heat transfer from one leg of a Wheatstone bridge	10 ppm to 100% H ₂	Cannot be effectively used when both He and H ₂ are present in a carrier gas.
Chemical Reaction	Combustion induces combustion in proximity of one leg of a Wheatstone bridge.	No independent system of this type exists. A gas chromatograph with a sonic detector using this principle can detect 50 ppm to 10% H ₂	Sample must be tested in non-hazardous environment. Cannot distinguish between hydrogen and other combustible gases, and concentrated oxidizers.
	Catalytic Combustion measures heat generated by catalytic combustion in proximity of one leg of a Wheatstone Bridge Fuel Cell electrical current is generated by the hydrogen fuel in the gas sample.	0.15 - 25% H ₂ with \pm 1% Full Scale accuracy. .1% H ₂ in air, lower limit at pressures from 1 mm hg to several psi (Prototype only.)	Cannot be used in an inert atmosphere without an air supply. Discrimination between hydrogen and propane tested good, but no data on other hydrocarbons.

TABLE II, Continued

Empirically Observed Physical Reactions	<u>Kryptonate 85</u> measures radioactivity of Kr85 released from Pt O ₂ in a hydrogen environment	0-3% in air 0-10% H ₂ in air response time less than 20 seconds	Cannot be exposed to atmosphere that reduces Pt O ₂
Fluid Flow Characteristics	<u>Fluidic</u> measures flow of sample gas	Conceptual stage of development -	It is anticipated that helium mixtures may be confused with hydrogen mixtures.
Permeability Into Other Materials	Palladium Tube Membrane - hydrogen permeates the membrane where it is ionized and the characteristic line radiation is measured.	Prototype only - no range known	Not known Note: membrane must be permeable to H ₂ only.

in binary mixtures. This is covered in the literature survey below.

Fluidic Detectors

The use of fluidic oscillators for gas detection is mentioned in the Boeing Report as a potential device for hydrogen detection. It seemed to our group that the apparent advantages are that it would provide a reliable, sensitive, and inexpensive detector, requiring little maintenance and calibration. It could also be easily adapted to the detection of hydrogen and/or helium. In addition these devices could be used in areas with vacuum lines, positive pressure gas lines, water lines, steam lines, etc. since through aspirator-ejectors the fluidic oscillator could be made to "sniff" its environment. Direct electrical readout of frequency changes and concentration, could be made of a fluidic oscillator frequency signal.

Many of these readings would be possible per second through the use of multiplexing devices. Reliability appears to be high and the possibility for use as a fire or hydrogen detector appears as a distinct possibility since the oscillator can be made sensitive to temperature changes of the entering gases.

In order to determine the current state of the art in fluidic gas detection a literature survey as well as personal contacts including visitations were conducted.

Literature Survey and Other Information Sources.

In order to obtain as clear a picture as possible the following companies were contacted in order to ascertain the state of the art:

General Electric	(Apollo Systems Development)
	(Specialty Fluidics)

Minneapolis - Honeywell

Bendix Corporation

McDonnell - Douglas Company

Aviation Electronics Limited

The Harry Diamond Laboratories

Corning

A few small companies and a few individuals.

Literature was obtained pertaining to these oscillators from recent fluidic conferences. In general, there appears to be no development effort in any of these companies in this area with one or two exceptions. The pertinent and significant works found are summarized:

D. E. Davis of the University of North Carolina has published an article, based upon his Ph.D. work done at the University of Florida, showing the strong dependence of the frequency of fluidic oscillators on the concentration of another gas in a binary mixture. The oscillator he used was of the partial feedback type. The results he obtained are shown in Fig 1. At the lower end, Davis obtained unusually large frequency variations for small change in H_2 concentrations, 8800 hz variation in fluidic oscillator frequency for a 6% change in H_2 concentration. This gives a scale factor of approximately 50 cps/ft/sec. or 7 ppm. The scale factor is used here as a measure of sensitivity of the fluidic oscillator to changes in the velocity of sound, in other words the scale factor is the ratio of the change in oscillator frequency (cps) divided by the change in the speed of sound (ft/sec). This scale factor is a constant for each device.

F. Villaroel and J. W. Joyce at the Harry Diamond Laboratories using an edgetone oscillator obtained the detection curves shown in Fig. 2, for the determination of the CO_2 concentration in air. It is

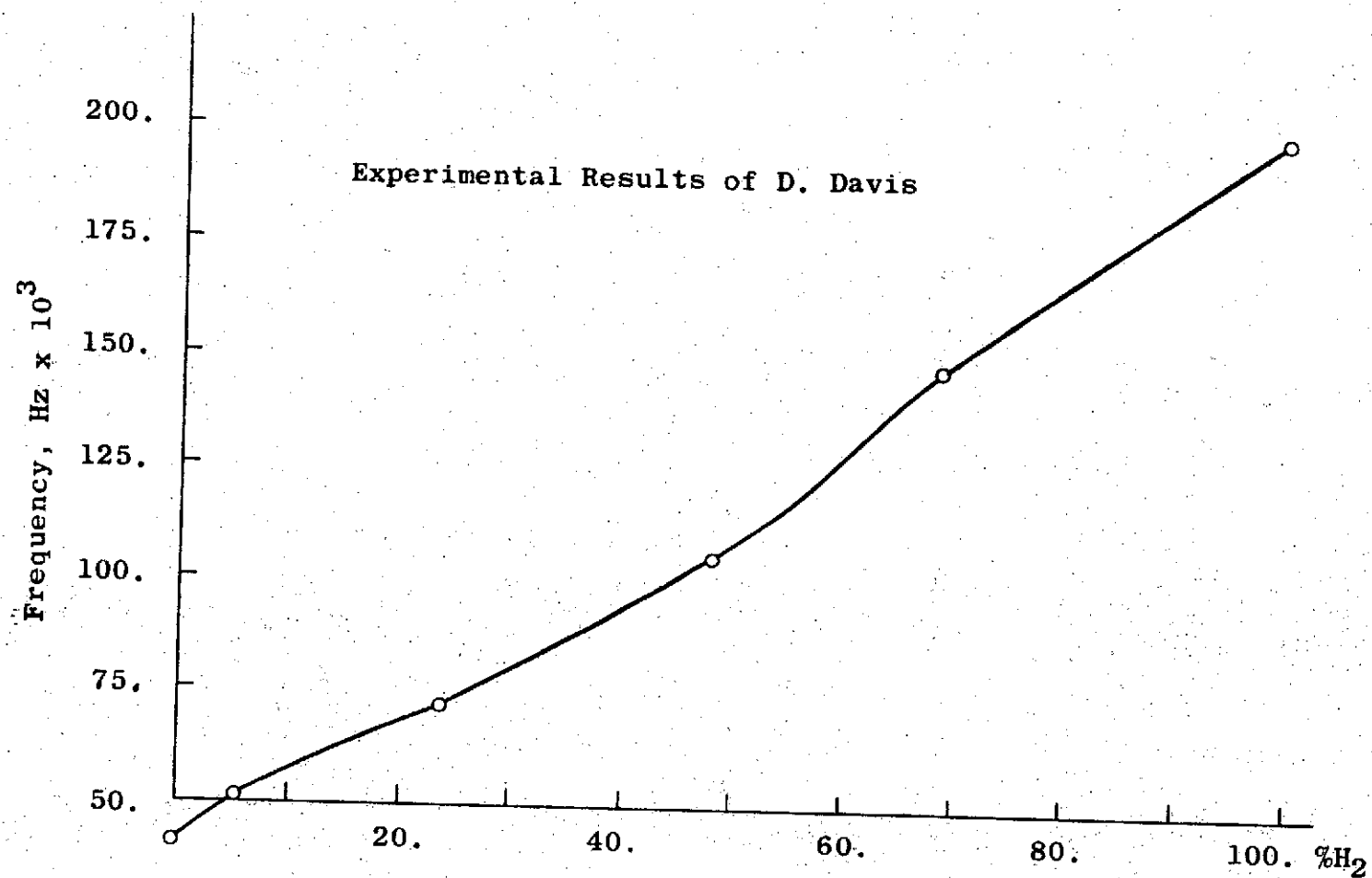


Fig. 1 Frequency versus H_2 Concentration in CO_2

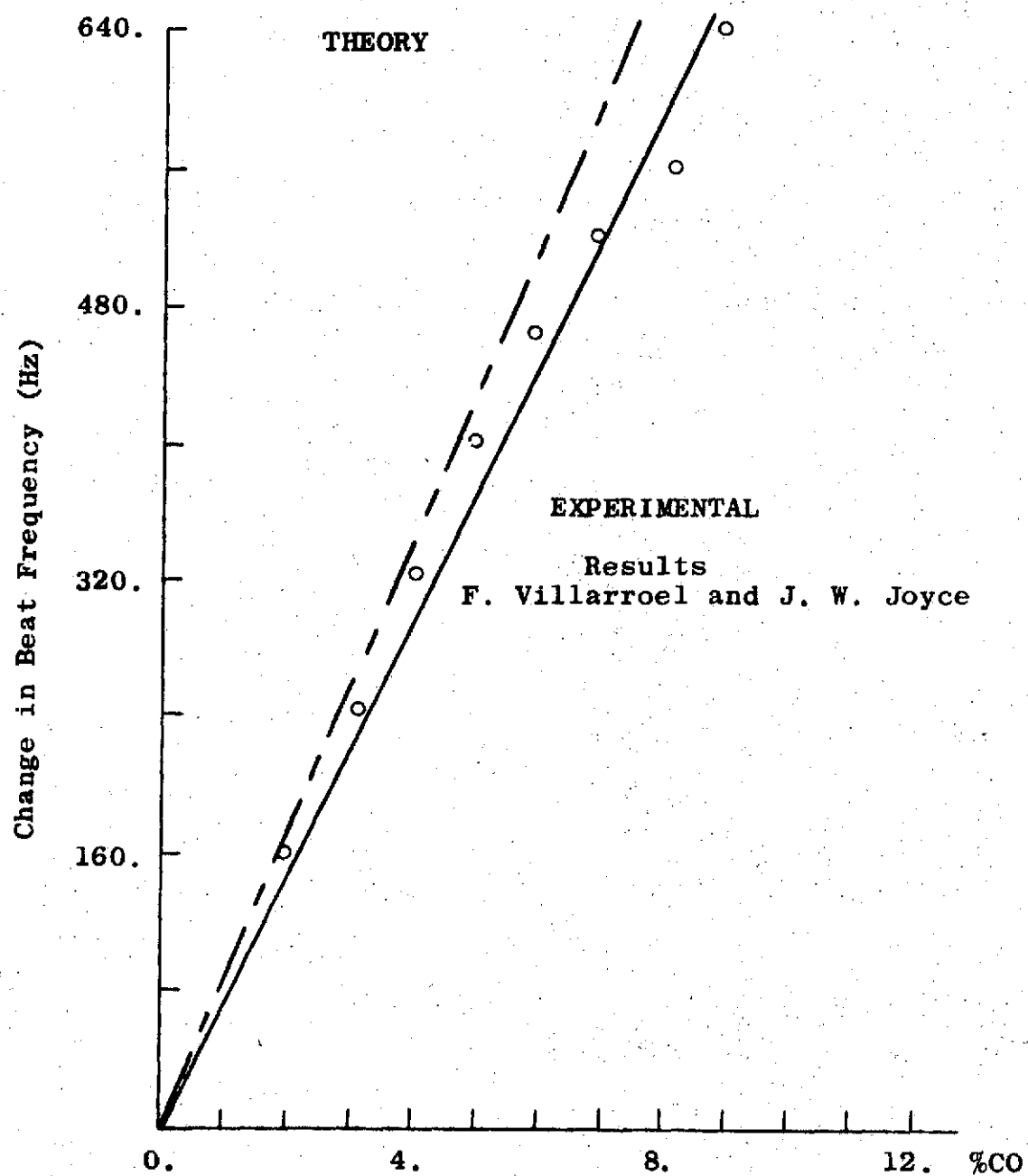


Fig. 2 Frequency versus CO₂ Concentration in Air

of interest to note that this carefully done work achieves a scale factor of approximately 30 cps/ft/sec. The authors describe using the output of two oscillators and beating them together to increase the sensitivity of the detector. They indicate the variation for a given mixture was ± 5 hz corresponding to a ± 0.1 percent CO_2 concentration change.

Work done by J. Simpson at McDonnell-Douglas involving the calibration of various pressure transducers showed that by varying the He concentration in N_2 from 0 - 100% he could achieve approximately a threefold change in the frequency using a fluidic oscillator. By changing the dimensions of the transducer he indicates he obtained a device which would oscillate over the range of 35 to 105 KHz. No curves are given of the variation in frequency versus the variation in He concentration.

The General Electric Company has done some work in this area and personnel there are well aware of the change in frequency caused by varying the amount of constituents in binary systems. Mr. Robert Rose at the Fluidic Specialty Group in Schenectady indicated that no contractual effort was underway in this area, though they had done work for the Navy on the use of an oscillator for O_2 detection.

Conclusion

As a result of this study, surveying the field, it was decided that the fluidic oscillator represented the sensor which had the greatest unexploited potential and therefore development and testing of this device should be initiated.

FLUIDIC OSCILLATORS

Introduction

The field of using the energy in fluid streams for doing work or controlling action or as sensing devices now referred to as FLUIDICS or FLUERICS is relatively new. It came into being some 20 years ago. The basis for many of the fluidic devices is the "Coanda" effect which first was utilized at that time by the founders of the Harry Diamond Laboratory. Since that time fluidic controls have proven themselves to be more rugged than electronic controls, yet faster, cheaper, and more reliable than the ordinary pneumatic or hydraulic controls.

The term "fluidics" has come to mean the control of one fluid stream (liquid or gas) by another stream. Unlike either pneumatic or hydraulic devices, fluidic devices have no moving parts to wear out. Because of the continuous flow through the device, most dust or water particles will tend to pass through without difficulty. As a result, these devices are very reliable and do not need continued or frequent adjustment.

The application of fluidics to the detection of gases has not been entirely unknown. Fluidic devices have been used to detect Carbon Dioxide variations in physiological experiments and in oxygen control systems for undersea applications. In each case the fluidic device oscillates at a base frequency as the normal gas constituents pass through. If there is any variation in the density of the gas due to a change in the amount of one constituent present, the frequency of oscillation will change.

This change is proportional to the inverse of the square root of

the density of the gas.

There are two basic types of oscillators which can be used in this application. These are shown in Fig. 3 and Fig. 4. The former is a proportional amplifier with a feedback loop, the latter is an edgetone oscillator.

These two devices have formed the basis for the fluidic gas detection devices and the capabilities for both these designs have been explored in this investigation. In addition to the partial feedback fluidic oscillator one was developed here employing very high momentum feedback, making the device much more stable and insensitive to environmental variations. Also the signal intensity is increased considerably allowing the signal to be translated into an electrical output without amplification being needed.

The performance characteristics of each of these devices is discussed below. For clarity of presentation the fluidic gas sensors are divided into two types. The F type which was the one with which most of the development work was done as a feedback oscillator with external feedback loops so that changes can be made easily and the effects of parameter variations studied and the resultant S series which are designed to have the desired characteristics. The other type is the M series which are the edgetone oscillators.

Oscillator Developments

Fig. 3 and Fig. 4 show the basic design of the fundamental types of oscillators which can be used as gas detectors. They are the feedback oscillator, basically a proportional fluidic amplifier with appropriate feedback loops, and the edgetone oscillator.

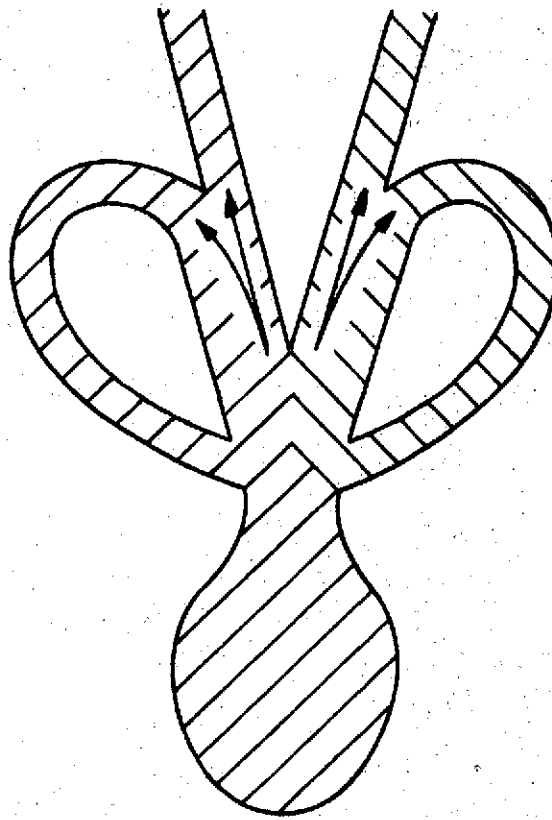


Fig. 3 Fluidic Feedback Oscillator

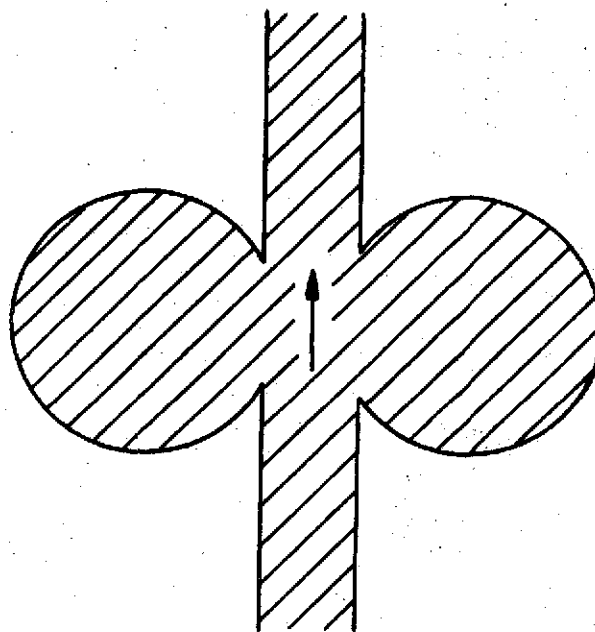


Fig. 4 Fluidic Edgetone Oscillator

Both types of oscillators were designed, tested and evaluated here at the University of Florida.

The F type of fluidic oscillator was designed from a Honeywell block of a proportional amplifier, which was modified and external feedback loops added. After preliminary experiments which indicated a sluggish, not very well behaved oscillator, it was decided to use the full stream as the feedback. This almost 100% momentum feedback with the excess air allowed to vent itself resulted in an extremely stable oscillator which would operate well over wide ranges of pressure differentials and allowing a tremendous range of density. It would oscillate with water and gases including H_2 , with correspondingly significant changes in oscillating frequency.

This fluidic oscillator proved to have a very constant frequency and to produce a signal of sufficient strength that it required no amplification. The S series oscillators were developed using the same principle as the F series. This new development was made because the frequency of oscillation of the F series was too low to provide directly the sensitivity needed to detect hydrogen concentrations as low as \pm 50 ppm.

The edgetone oscillator was given the designation M and the series was constructed as shown in Fig. 4. Both of these oscillators could reach frequencies up to 60,000 Hz with pure hydrogen gas.

In order to describe each oscillator, the following sections are devoted in turn to the F-S series and then the M series of fluidic oscillators. The presentation below includes theory, test results and evaluation of the gas sensors.

Theory of Operation

The fluidic oscillator, a fluidic amplifier with feedback loops is essentially a combination of properly proportioned fluid passages, the behavior of which is described by the basic fluid flow equations.

Conservation of Energy

Conservation of Momentum

Equation of State

and for convenience

Equation of Continuity

Conservation of Energy

To account for all the energy entering, leaving and being transformed in a fluid stream leads to the conservation of energy equation which can be written in the following form:

$$c \frac{dh}{dt} - \frac{dP}{dt} + \frac{c}{2} \frac{d}{dt} (u^2 + v^2 + w^2) =$$

$$\left[\frac{\partial}{\partial x} (k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (k \frac{\partial T}{\partial z}) \right] +$$

$$c(u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} + w \frac{\partial h}{\partial z}) + \Phi - (u \frac{\partial P}{\partial x} + v \frac{\partial P}{\partial y} + w \frac{\partial P}{\partial z})$$

where

$$\Phi$$

is

$$\Phi = 2\mu \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial w}{\partial z} \right)^2 \right] - \frac{2}{3} \mu (\nabla \cdot \vec{V})^2$$

$$+ \mu \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 + \mu \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right)^2 + \mu \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right)^2 \quad (1)$$

Conservation of Momentum

From Newton's Second Law which states that the resultant force acting on systems is proportional to the time rate change of momentum fluid in a volume V , the equation for conservation of momentum in the three coordinate directions can be written as follows:

$$\rho \frac{du}{dt} = \rho f_x - \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left[2\mu \frac{\partial u}{\partial x} - \frac{2}{3}\mu \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \right] \\ + \frac{\partial}{\partial y} \left[\mu \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right] + \frac{\partial}{\partial z} \left[\mu \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right) \right]$$

$$\rho \frac{dv}{dt} = \rho f_y - \frac{\partial p}{\partial y} + \frac{\partial}{\partial y} \left[2\mu \frac{\partial v}{\partial y} - \frac{2}{3}\mu \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \right] \\ + \frac{\partial}{\partial x} \left[\mu \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right] + \frac{\partial}{\partial z} \left[\mu \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) \right]$$

$$\rho \frac{dw}{dt} = \rho f_z - \frac{\partial p}{\partial z} + \frac{\partial}{\partial z} \left[2\mu \frac{\partial w}{\partial z} - \frac{2}{3}\mu \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \right] \\ + \frac{\partial}{\partial x} \left[\mu \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right) \right] + \frac{\partial}{\partial y} \left[\mu \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) \right]$$

where

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z} \quad (2)$$

Equation of State

For real substances the equation of state which accurately describes the behavior of the substance can become extremely complicated.

For our purposes here reasonable results can be obtained by considering

$$e = \psi(P, T) \quad (3)$$

which will prove to be sufficiently precise to describe the behavior of oscillators considered in this report.

Continuity Equation

The conservation of mass which is the basis of the continuity equation simplifies the theoretical treatment of the oscillators. It can be written as follows:

$$\frac{\partial e}{\partial t} + \frac{\partial e u}{\partial x} + \frac{\partial e v}{\partial y} + \frac{\partial e w}{\partial z} = 0 \quad (4)$$

All the above equations can be written in vector or tensor form, in cylindrical or other coordinates to make them more convenient and adaptable to use in specific applications.

Although none of the equations can be solved as a group as written above, by using some simplifying assumptions they can be solved either by computer or in closed form. Reasonably accurate results can then be obtained.

This is done in the following sections to arrive at an analytical representation for a fluidic oscillator's response under different conditions.

Propagation of Waves in Fluid Lines

A simplified

form of the energy equation in two dimensions can be written as

$$\int_V \frac{\partial}{\partial t} e \left(u + \frac{v^2}{2} \right) dV + \int_A e \left(u + \frac{v^2}{2} + \frac{p}{\rho} \right) \tilde{V} \cdot \tilde{n} dA \\ + \int_A \tilde{q} \cdot \tilde{n} dA = \int_V e \tilde{f} \cdot \tilde{V} dV + \int_V \Phi dV$$

where

$$\Phi = 2\mu \left[\left(\frac{\partial v_r}{\partial r} \right)^2 + \left(\frac{v_r}{r} \right)^2 + \left(\frac{\partial v_\theta}{\partial \theta} \right)^2 \right] + \mu \left(\frac{\partial v_r}{\partial \theta} + \frac{\partial v_\theta}{\partial r} \right)^2 \quad (5)$$

The expression describing the change in mechanical power dP_m over the distance dz is

$$dP_m = \dot{m} d \left(\overline{\int \frac{dp}{\rho} + \frac{v^2}{2}} \right) \\ = \dot{m} d\epsilon \quad (6)$$

Assuming small pressure and velocity changes the equations can be linearized by assuming the following variations in ρ and v_g

$$e = \bar{e} + e'$$

$$v_z = \bar{v}_z + v'_z$$

$$\frac{\partial e}{\partial \tau} + \frac{1}{r} \frac{\partial}{\partial r} e r v_r + \frac{\partial}{\partial z} e v_z = 0$$

Assuming the wavelength λ is large compared to the radius r of the tube one can obtain the energy equation as follows:

$$\frac{\partial e'}{\partial \tau} + \bar{e} \frac{\partial v'_z}{\partial z} = 0 \quad (10)$$

$$\lambda = \frac{2\pi |c|}{\omega} \gg r_w$$

where $|c|$ is the complex speed of wave propagation and for small fluctuations in the fluid velocity v

$$\frac{P}{e\tau} = \beta e \int \frac{ds_i}{c v} \cong \text{const.}$$

since $\nabla^2 \tilde{v}$ in S term appears as squares, its contribution for small v can be considered negligible.

$$\frac{\partial e'}{\partial r} = \frac{\partial e'}{\partial P} \frac{\partial P}{\partial r} = \frac{1}{a^2} \frac{dP'}{dr}$$

and

finally the energy equation can be expressed as

$$\frac{1}{a^2} \frac{dP'}{dr} + \bar{e} \frac{\partial \bar{v}_z'}{\partial z} = 0 \quad (11)$$

It is now necessary to find a relationship between P' and \bar{v}_z' . This can be done through the use of the two dimensional form of the equation of motion in cylindrical coordinates.

$$\bar{e} \frac{\partial \bar{v}_z'}{\partial r} = - \frac{\partial \bar{P}'}{\partial z} + \frac{1}{\pi R_N^2} \int_0^{R_N} 2\pi \mu \frac{\partial}{\partial r} \left(r \frac{\partial \bar{v}_z'}{\partial r} \right) dr \quad (12)$$

In order to simplify the above expression, let us assume that

$$\mu \frac{\partial \bar{v}_z'}{\partial r} \Big|_{r=R_N} = - \frac{\tau_w}{R_N}$$

$$\bar{e} \frac{\partial \bar{v}_z'}{\partial r} = - \frac{\partial \bar{P}'}{\partial z} - 2 \frac{\tau_w}{R_N} \quad (13)$$

For fully developed incompressible flow, from the Hagen-Poiseuille equation

$$\frac{1}{\lambda_N}' = \frac{4\mu \bar{v}_z'}{\lambda_N}$$

$$\frac{1}{\lambda_N} = c_f \frac{1}{\lambda_N}'$$

Substituting into equation (12) and with the above assumptions one finds the momentum equation can be expanded as

$$\bar{e} \frac{\partial \bar{v}_z'}{\partial r} = - \frac{\partial \bar{P}'}{\partial r} - \frac{8 c_f \mu \bar{v}_z'}{\lambda_N^2} \quad (14)$$

and making use of the following relationships

$$\dot{m} = \bar{e} A \bar{v}_z'$$

$$e \approx \frac{\bar{P}'}{\bar{e}}$$

$$Le = \frac{1}{\bar{e} A}$$

$$Re = \frac{8 c_f \mu \pi}{\bar{e}^2 A^2}$$

$$A = \pi \lambda_N^2$$

(14a)

The momentum equation can finally be expressed as

$$L_e \frac{\partial \dot{m}}{\partial z} = - \frac{\partial \epsilon}{\partial z} - R_e \dot{m} \quad (15)$$

Substitution of equation (14a) into (11) and averaging one obtains equation (11) in the following form

$$\frac{\partial \epsilon}{\partial z} + \frac{1}{C_e} \frac{\partial \dot{m}}{\partial z} = 0 \quad (16)$$

$$C_e = \frac{\bar{e} A}{a^2}$$

Taking the Laplace Transforms of equations (15) and (16)

where

$$E(s) = \mathcal{L}[\epsilon(t)]$$

$$M(s) = \mathcal{L}[\dot{m}(t)]$$

$$\left. \begin{aligned} \frac{\partial E}{\partial z} - (R_e + s L_e) M &= 0 \\ \frac{\partial M}{\partial z} + s C_e E &= 0 \end{aligned} \right\} \quad (21)$$

This system when solved and inverted gives the familiar form of the wave equation

$$\frac{\partial^2 \epsilon}{\partial z^2} = c_e R_e \frac{\partial \epsilon}{\partial \tau} - c_e L_e \frac{\partial^2 \epsilon}{\partial \tau^2} \quad (22)$$

where ϵ is the mechanical potential.

Letting

$$\epsilon = \epsilon_0 e^{i\omega(\tau - \frac{z}{c})}$$

one obtains

$$\frac{\omega^2}{c^2} = L_e c_e \omega^2 - i\omega R_e c_e$$

and the complex speed of wave propagation is

$$\begin{aligned} |c| &= \frac{1}{(L_e c_e)^{\frac{1}{2}} \left(1 + \frac{R_e}{\omega^2 L_e}\right)^{\frac{1}{4}}} \\ &= \frac{a}{\left(1 + \frac{R_e}{\omega^2 L_e}\right)^{\frac{1}{4}}} \end{aligned} \quad (23)$$

From equation (23) it can be seen that the wave propagation in a pipe reaches a limit of and equal to the velocity of sound when the resistance in the pipe is zero. In general the velocity will be smaller than that of the speed of sound.

In the course of the above derivation, quantities such as L , R and C the inductance, resistance and capacitance for fluid lines were deferred. These quantities are further elaborated upon below so that practical evaluations can be made.

Fluidic Systems

Circuit elements and components are the least common denominators in the fluidic field which are interconnected to form circuits. The designer considering the development of a fluidic system must realize that most active fluidic devices are brought to function by set and try methods. Comprehensive analysis had led to useful empirical formulae and design criteria which define the interdependence of the supply and control jets upon each other and their mutual dependence on the interaction region, geometry, aspect ratios, output configuration, and loading. Only computers can cope with the mathematics involved with purely analytical design of fluidic components.

Passive elements in fluidic circuits such as restrictors, lines, capacitors, and inductors are generally needed when assembling fluidic elements in analog circuits. Thus mass flow is considered analogous to current and pressure analogous to voltage. A fluid impedance produces a pressure drop as a function of flow through it.

Fluid impedances are generated as in analogous electrical circuits by resistance, capacitance and inductance. Simple orifices are generally used to make fluid resistance. It should be noted that when orifices

are used with low pressure gases or incompressible fluids, their pressure flow characteristics follow the square law relationship, and hence are non-linear. In a pure capacitive fluid impedance, the pressure drop lags the flow by a phase angle of 90 degrees. Only compressible fluids show capacitive effects and in low pressure designs capacitive effects on most liquids are neglected. The analog of the electrical capacitor is simply a volume. Shunt capacitance is the only type that can be obtained without moving parts. Series capacitance (coupling capacitance) requires a diaphragm. In an inductor, the pressure drop leads the flow by a phase angle of 90 degrees. An acceptable fluid inductor can be made from long tubes.

Resistance

Orifices are often used for resistors because they are so easily constructed. From incompressible relationships, which are adequate over typical operating ranges, the weight flow rate may be obtained from

$$\dot{w} = C_d C A v$$

The velocity v is obtained from the incompressible relation

$$v = \left(2g \frac{\Delta P}{e} \right)^{\frac{1}{2}}$$

where ΔP is the pressure drop across the orifice. Using the perfect gas relationship, one finds

$$\dot{w} = A \left(\frac{2g P \Delta P}{R_g T} \right)^{\frac{1}{2}}$$

The resistance R may then be obtained as

$$R = \frac{\partial \Delta P}{\partial \dot{w}} = \frac{1}{A} \left(\frac{2 R_g T \Delta P}{g P} \right)^{\frac{1}{2}} \quad (24)$$

Laminar resistance is another manner in which a resistance can be generated. This is provided by laminar flow in long, small diameter passages. Calculation of resistance using incompressible flow relationships give sufficient accuracy if the pressure drop is not large.

Laminar flow requires that the Reynolds number be somewhat less than the critical. Assuming that a fully developed laminar flow exists over the flow length l , the expression for the resistance may be shown to be:

$$R = \frac{2(\Delta P)}{2N} = \frac{32 \mu l}{A D^2 e}$$

or

$$R = \frac{32 \mu l R_g T}{A D^2 e} \quad (25)$$

where A is the flow area and D the hydraulic diameter, that is

$$D = \frac{4A}{P}$$

where P is the wetted perimeter.

Capacitors

In fluidic circuits which use gas as the operating medium, the gas compressibility results in energy storage analogous to that of a capacitor in an electronic circuit. Hence, the fluidic capacitor is simply a volume for gas storage.

Using Laplacian notation, it can be shown that

$$\dot{w} = \left(\frac{C_v V_1}{C_p R_g T_s} \right) s P_1$$

since

$$\frac{C_p}{C_v} = k$$

$$P_1 = \frac{k R_g T_s}{V_1 \left(\frac{\dot{w}}{s} \right)}$$

or

$$= \dot{w}_s / C_1 s$$

where the capacitance

$$C_1 = \frac{V_1}{k R_g T_s} \quad (26)$$

Inductors

The fluids in fluidic passageways also have inertial properties or inertance which can significantly effect dynamic characteristics. The inertial effects which are present for both compressible and incompressible fluid result in characteristics similar to inductance in electrical circuits. In this case, it can be shown that:

$$\Delta P = \frac{l}{A g} \frac{d\dot{w}}{dt}$$

using Laplace notation

$$\Delta P = L s (\Delta \dot{w})$$

where the inductance

$$L = \frac{l}{g A}$$

with A the crossectional area.

With some of the characteristic behavior of fluidic circuit components discussed fluidic circuits can be designed with desired characteristics. One group of such circuits are the fluidic oscillators.

Feedback Fluidic Oscillators

The basic principle of operation can be seen from the design in Fig. 3 which shows a main channel or nozzle through which the fluid enters. Leaving the nozzle it has two exit channels to choose from. Some inherent imbalance and the Coanda-effect will make it flow through one of the channels. As it does so an appropriate portion of the fluid is recirculated through the feedback loop and pushes the main fluid stream to the other side. Now exiting through the other channel, fluid is fed back through the second feedback loop and pushes the main stream back to the original position. In this manner the main stream is switched back and forth producing the oscillations.

The nozzle may be convergent or convergent - divergent to allow the oscillator to operate subsonically or supersonically.

From the standard fluid flow analysis (assuming perfect gas behavior), knowing the conditions the oscillator operates between, all nozzle exit conditions n, P, T, v, V , etc., can be calculated.

Using the

Conservation Energy

Conservation of Momentum

Equation of State

and

Continuity Equation where convenient

and using the Mach number (M) as the basic parameter, defined as

$$M = \frac{v}{a}$$

the exit conditions can be determined

$$T = T_0 \frac{1}{1 + \frac{\gamma-1}{2} M^2} \quad (28)$$

$$P = P_0 \left(1 + \frac{\gamma-1}{2} M^2\right)^{-\frac{\gamma}{\gamma-1}} \quad (29)$$

$$\rho = \rho_0 \left(1 + \frac{\gamma-1}{2} M^2\right)^{-\frac{1}{\gamma-1}} \quad (30)$$

$$V = a_{Th} M \left(\frac{\frac{\gamma+1}{2}}{1 + \frac{\gamma-1}{2} M^2} \right)^{\frac{1}{2}} \quad (31)$$

$$A = A_{Th} \frac{1}{M} \left(\frac{1 + \frac{\gamma-1}{2} M^2}{\frac{\gamma+1}{2}} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (32)$$

And more relationships could be worked out.

If the losses are negligible in the nozzle as they usually are the actual values can be determined without extensive calculations from "isentropic" flow tables (Gas Tables, Keenan & Keye, Wiley).

The gas or gas mixture exiting from the nozzle travels through the channel which divides into the two exits from which the feedback channels branch off.

Since these channels are essentially $A = C$ (although varying areas can be treated) the flow through them can be considered Fanno Flow.

Again using the basic equations, the properties of the flowing gas mixture can be determined for the quasi-steady state existing in the channels.

Since we have losses in this case (they may however be small) the stagnation pressure changes.

$$P^0 = P_1^0 \frac{M_1}{M} \left(\frac{1 + \frac{\gamma-1}{2} M^2}{1 + \frac{\gamma-1}{2} M_1^2} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (33A)$$

or in terms of a drag coefficient

$$P^0 = P_1^0 \frac{1 + \gamma \left(1 - \frac{C_D}{2}\right) M_1^2}{1 + \gamma M^2} \quad (33B)$$

or in terms of thermodynamic quantities

$$P^0 = P_1^0 e^{\frac{S_1 - S}{R/T}} \quad (33C)$$

If the channel is long enough M will become 1 at the exit and with this condition taken as reference:

$$T = T^* \frac{\frac{\gamma+1}{2}}{1 + \frac{\gamma-1}{2} M^2} \quad (34)$$

$$P = P^* \frac{1}{M} \left(\frac{\frac{\gamma+1}{2}}{1 + \frac{\gamma-1}{2} M^2} \right)^{\frac{1}{2}} \quad (35)$$

$$e = e^* \frac{1}{M} \left(\frac{1 + \frac{\gamma-1}{2} M^2}{\frac{\gamma+1}{2}} \right)^{\frac{1}{2}} \quad (36)$$

$$v = v^* M \left(\frac{\frac{\gamma+1}{2}}{1 + \frac{\gamma-1}{2} M^2} \right)^{\frac{1}{2}} \quad (37)$$

Again these equations have been worked out and the results are available in ratio form in the gas tables. If the proper γ is used for the mixture at hand interpolation will give good results.

The feedback loops which control the oscillations of the device can be designed as a $R-C-R$ system involving resistances, capacitance and inductance (a channel, a cavity and a channel again) the characteristics of the oscillator and its sensitivity to environmental parameters can be controlled.

Fig. 5.

The $a's$ are the respective crosssectional areas and the $l's$ the respective length of the channels.

Any flow change in the feedback loop due to a change in temperature or pressure (the most common variable parameters) can be controlled, amplified or cancelled out by the proper choice of R_1 , C , and R_2 so that the pulse switching the nozzle jet arrives still at the required time at the exit of the feedback loop.

In this manner the oscillator can be made insensitive to temperature changes, to pressure changes or both. In other words the oscillation frequency becomes a function of concentration only.

On the other hand if it is desired the fluidic oscillator can be made a temperature sensor or pressure sensor.

The first feedback oscillator which was constructed for this study utilized a Honeywell proportional fluidic amplifier block, modified by blocking some of the passages and adding new ones and providing for external feedback loops so that changes in design can be made and their effects studied. The fundamental frequency of oscillation or the number of pulses from each exhaust port is

$$f = \frac{N_{FB}}{2 l_{FB}}$$

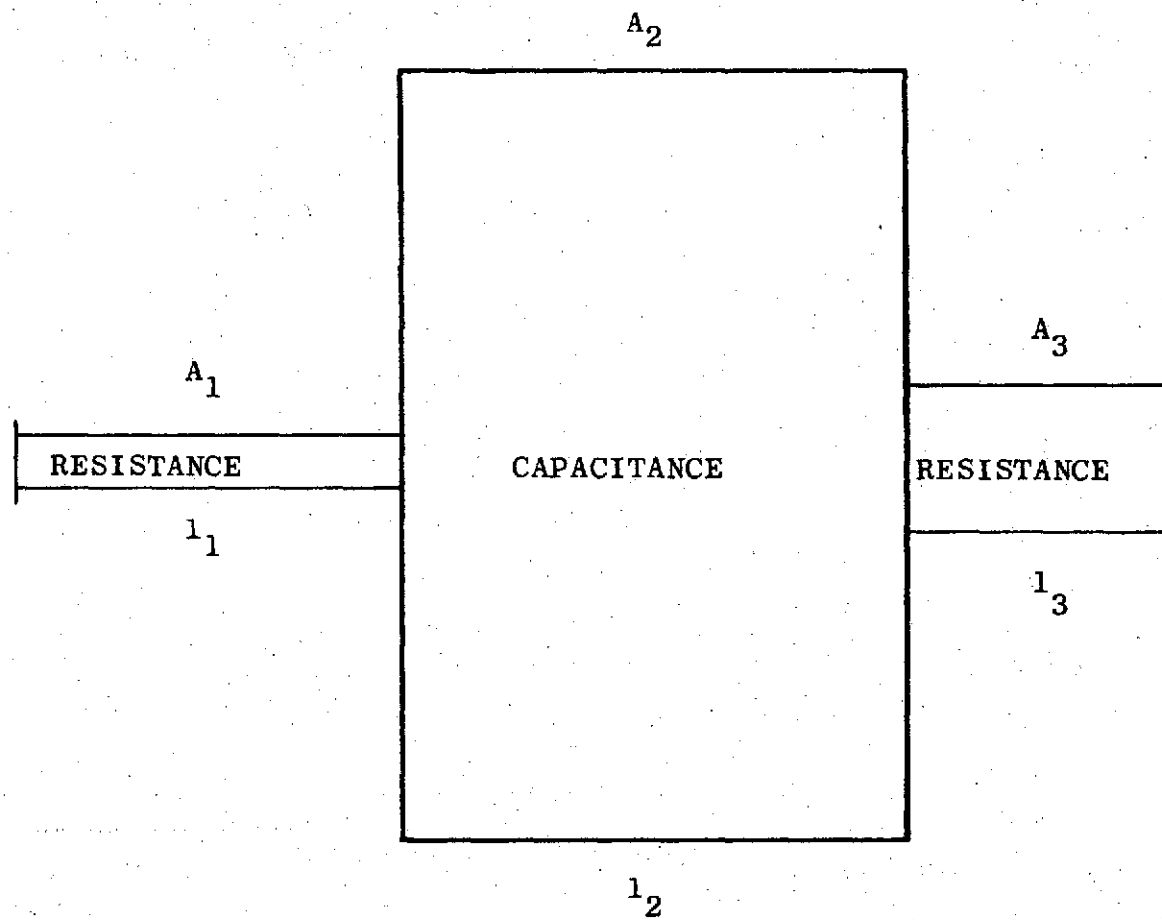


Fig. 5 R-C-R Feedback Loop

Fig. 6 shows this oscillator designated F-1 with its channels and feedback loops. Transparent cover sheets were provided so that the operation could be studied with smoke making the flow patterns visible. This oscillator can be operated under positive pressure or by providing a vacuum at the outlet, the latter operation was used when it was used as a gas sensor.

Some of the channel detail is shown in Fig. 7. It is seen that the main flow stream is fed back (Fig. 6) so that good stability and high amplitude signal output could be obtained. This oscillator produces a clearly audible signal. Fig. 8 shows this same oscillator with variable resistances and variable capacitances added to the feedback loops so that the fluidic oscillator characteristics could be controlled and made to behave properly and make the frequency respond to the various parameters as desired.

The general test set-up to determine the performance of the oscillator is seen in Fig. 9 and Fig. 10. Detail of the experimental equipment will be discussed later. At this time it is sufficient to state that it was possible to obtain the oscillator performance with air, N_2 , He, H_2 , O_2 , CH_4 , and mixtures of these gases, to do this with varying pressure differentials across the oscillators and both under positive pressure and with a vacuum applied. Other variables such as temperature variations, wind gusts, etc., could also be introduced.

The pressure pulses produced by the fluidic oscillators were changed into electrical signals through a number of transducers both magnetic and crystal and the cheapest and most satisfactory one was the earphone of a transistor radio. The signal produced by the F-1 Fluidic oscillator and changed into an electrical signal by a transistor radio

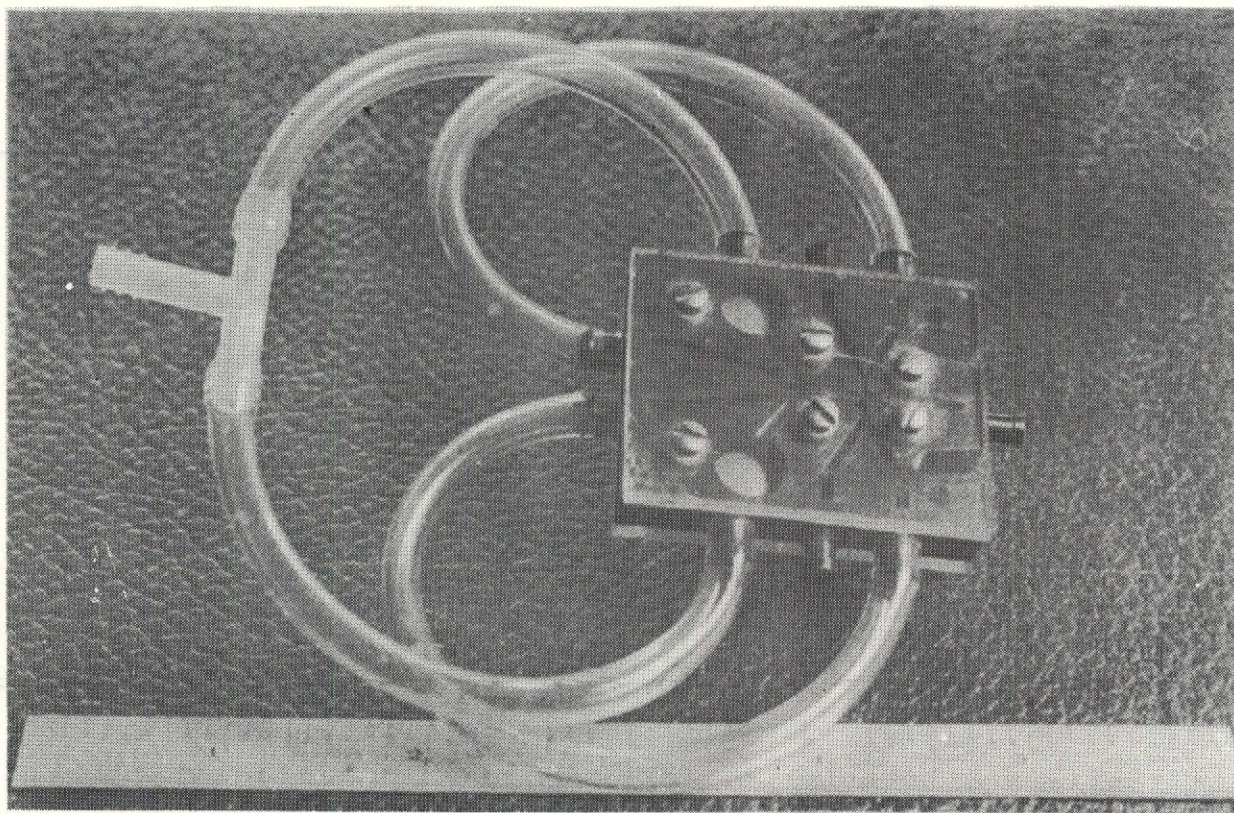


Fig. 6 F-1 Feedback Oscillator

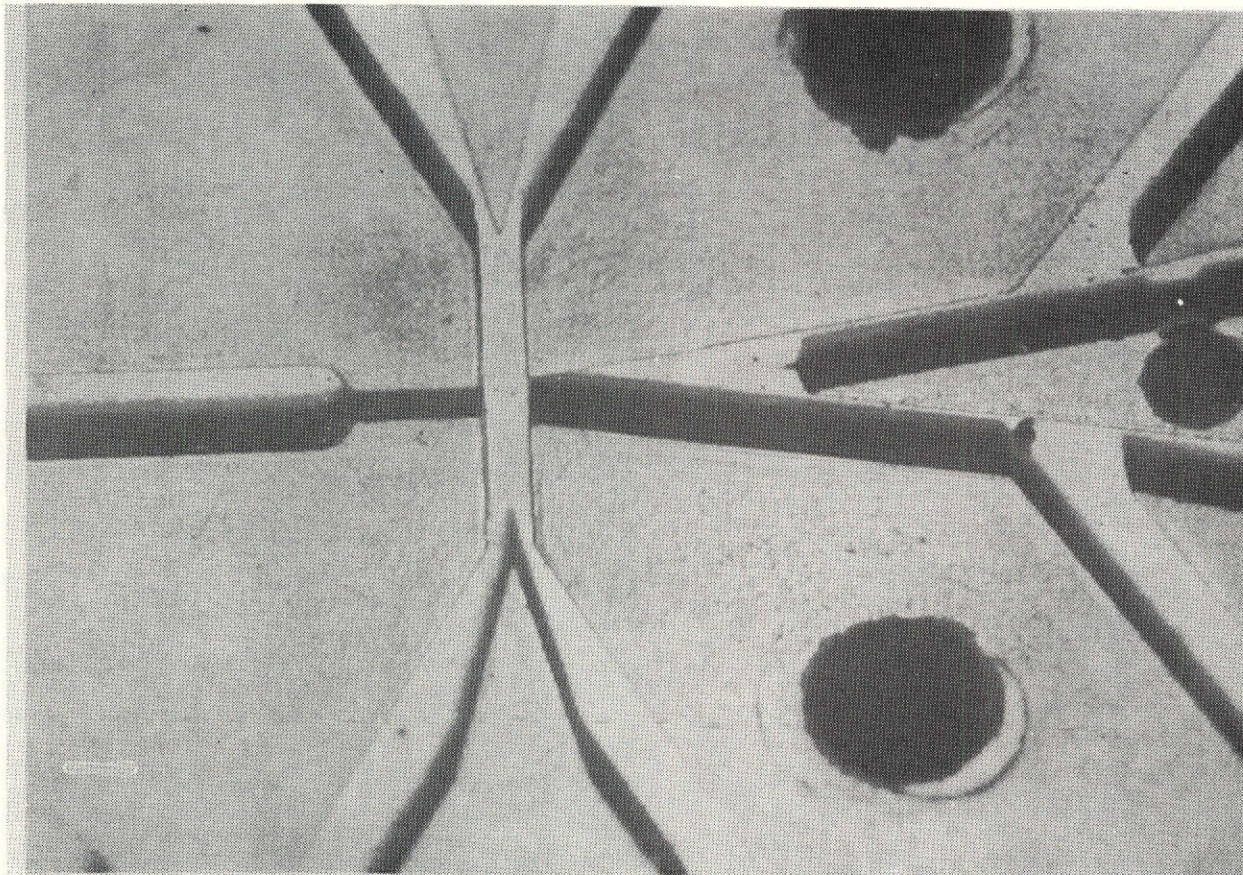


Fig. 7 F-1 Oscillator Channel Detail

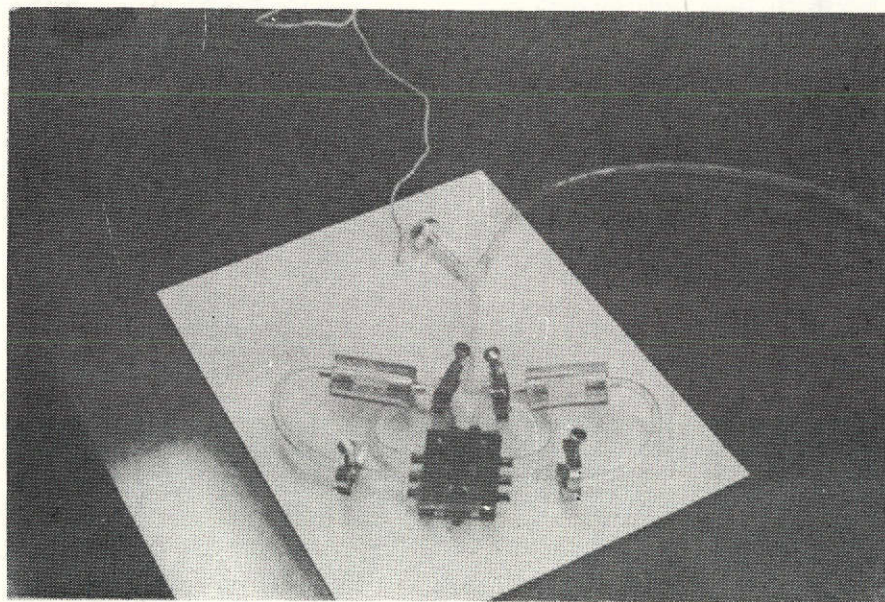


Fig. 8 F-1 Fluidic Feedback Oscillator with
Variable R-C-R Feedback Loops

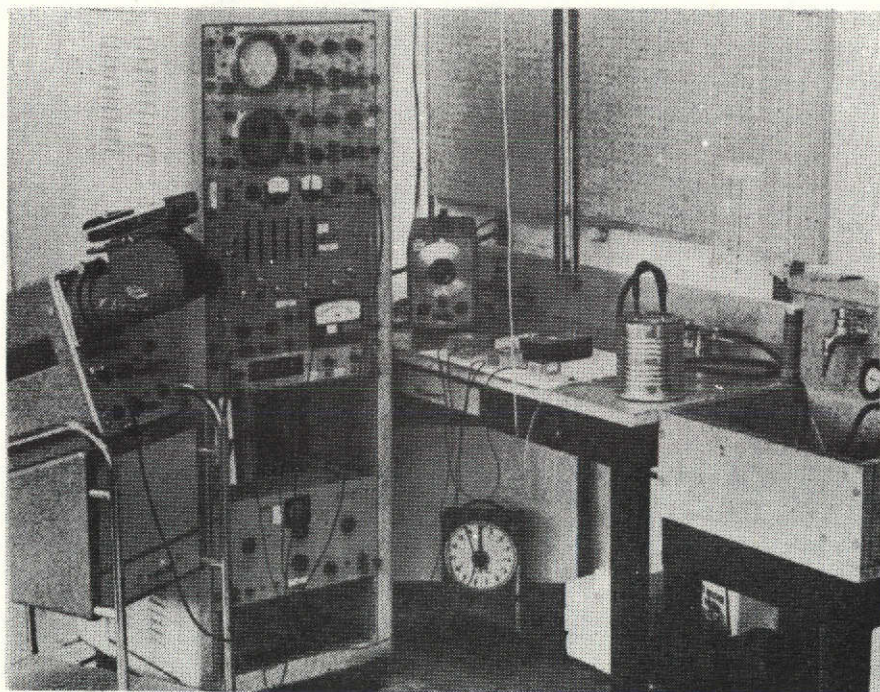


Fig. 9 Evaluation Test Set-up

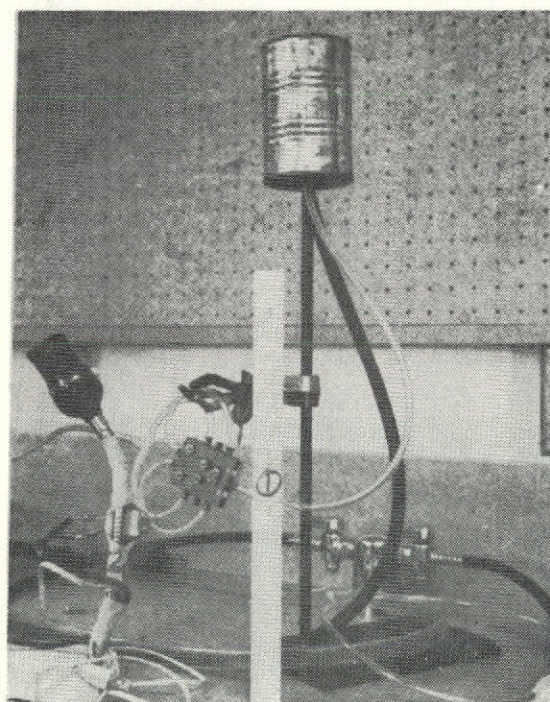


Fig. 10 Test Set-up Close-up

earphone and displayed on an oscilloscope is shown in Fig. 11 for air with a pressure differential of 1 inch of Hg and in Fig. 12 for CH_4 . It should be noted that in the examples shown that oscillations were nearly pure sine waves.

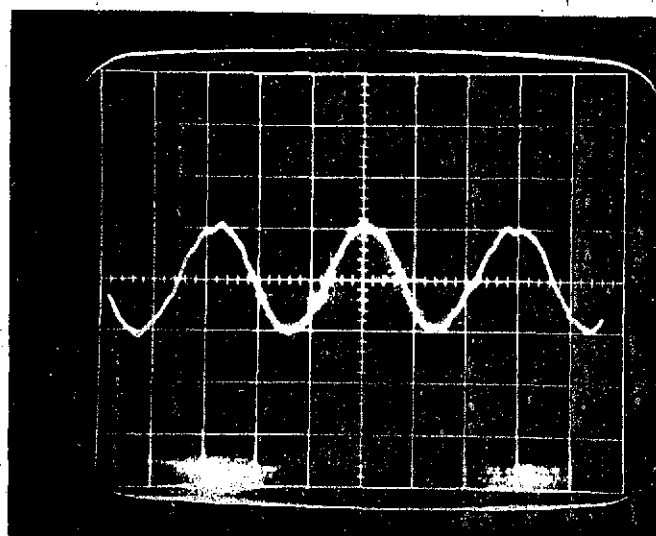
Tests conducted using the F-1 fluidic oscillator to determine the response of the oscillator as the pressure drop across it is increased is shown in Fig. 13 where the typical square root response curve is obtained.

Further experiments of this type to determine the response to natural gas are shown in Fig. 14.

The oscillation frequency of the F-1 oscillator was rather low because of the long external feedback loops. To increase the sensitivity of the oscillators the frequency of oscillation must be increased. The easiest way to do this is to shorten the feedback loop lengths. For this reason the F-1 oscillator was modified and the external feedback loops replaced by channels cut into the oscillator block. This shortened the distance the switching signal had to travel and more than doubled the oscillation frequency.

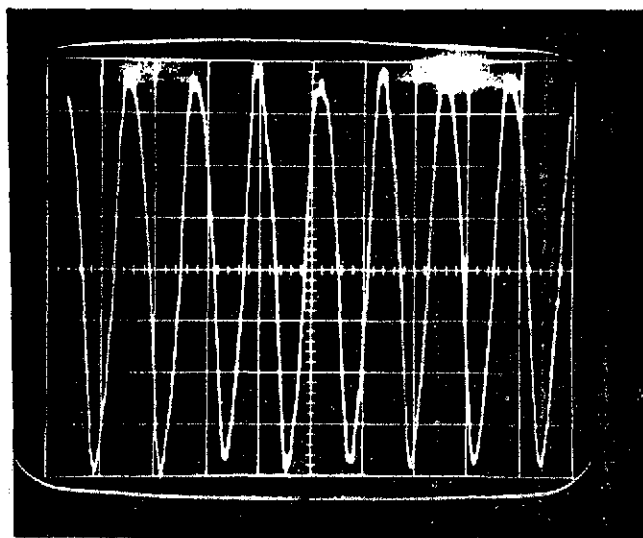
This design was designated as the F-2 series and the signals obtained from this unit is shown in Fig. 15 for air and in Fig. 16 for natural gas.

Tests were conducted with the F-2 oscillators using the bell jar mixing chamber shown in Fig. 17 and Fig. 18 to determine the response of this oscillator to varying concentrations of CH_4 . The bell jar allowed the exact measuring out of gas volumes and the stirring motor inside kept them well mixed. The results of these tests are presented in Fig. 19.



(unfiltered)

Fig. 11 F-1 Signal Trace, Air



(unfiltered)

Fig. 12 F-1 Signal Trace, CH₄

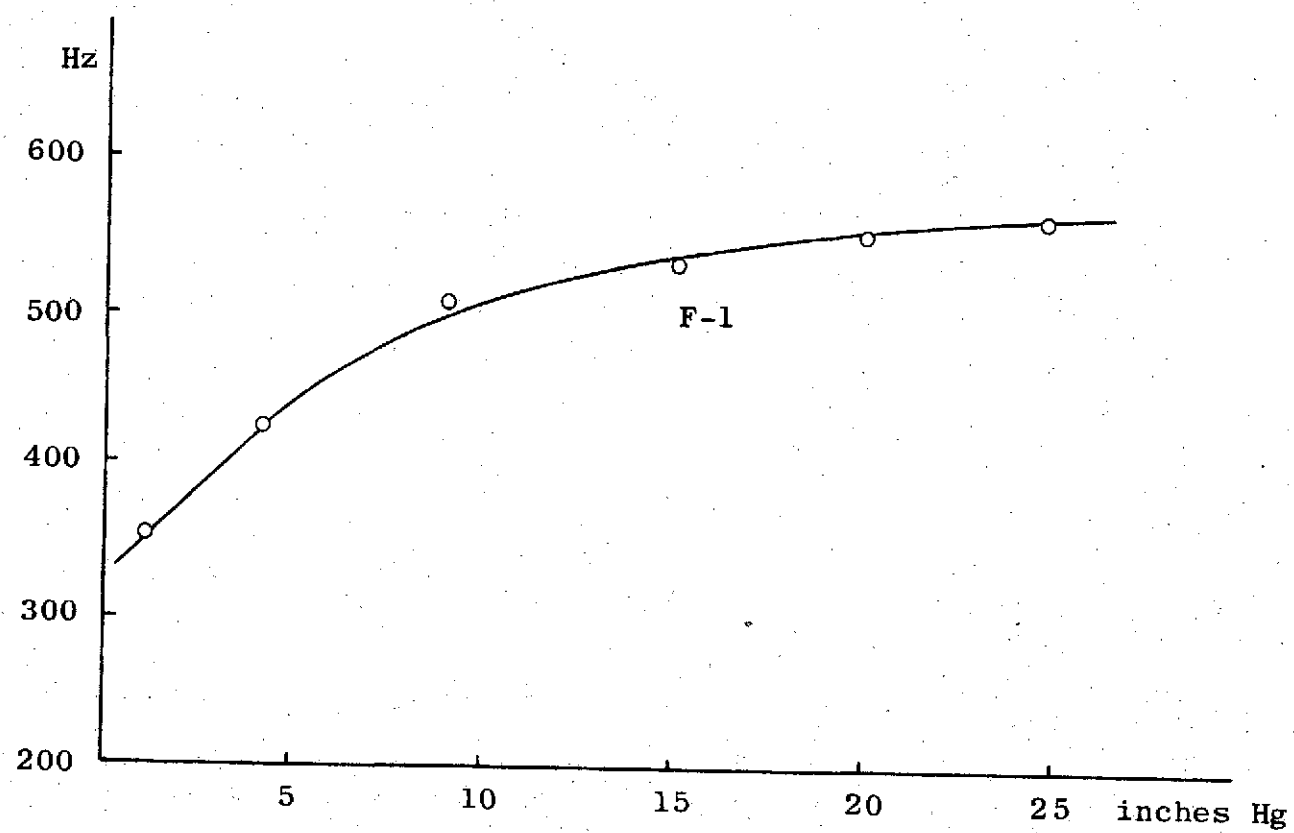


Fig. 13 F-1 Frequency versus Pressure Differential, Air

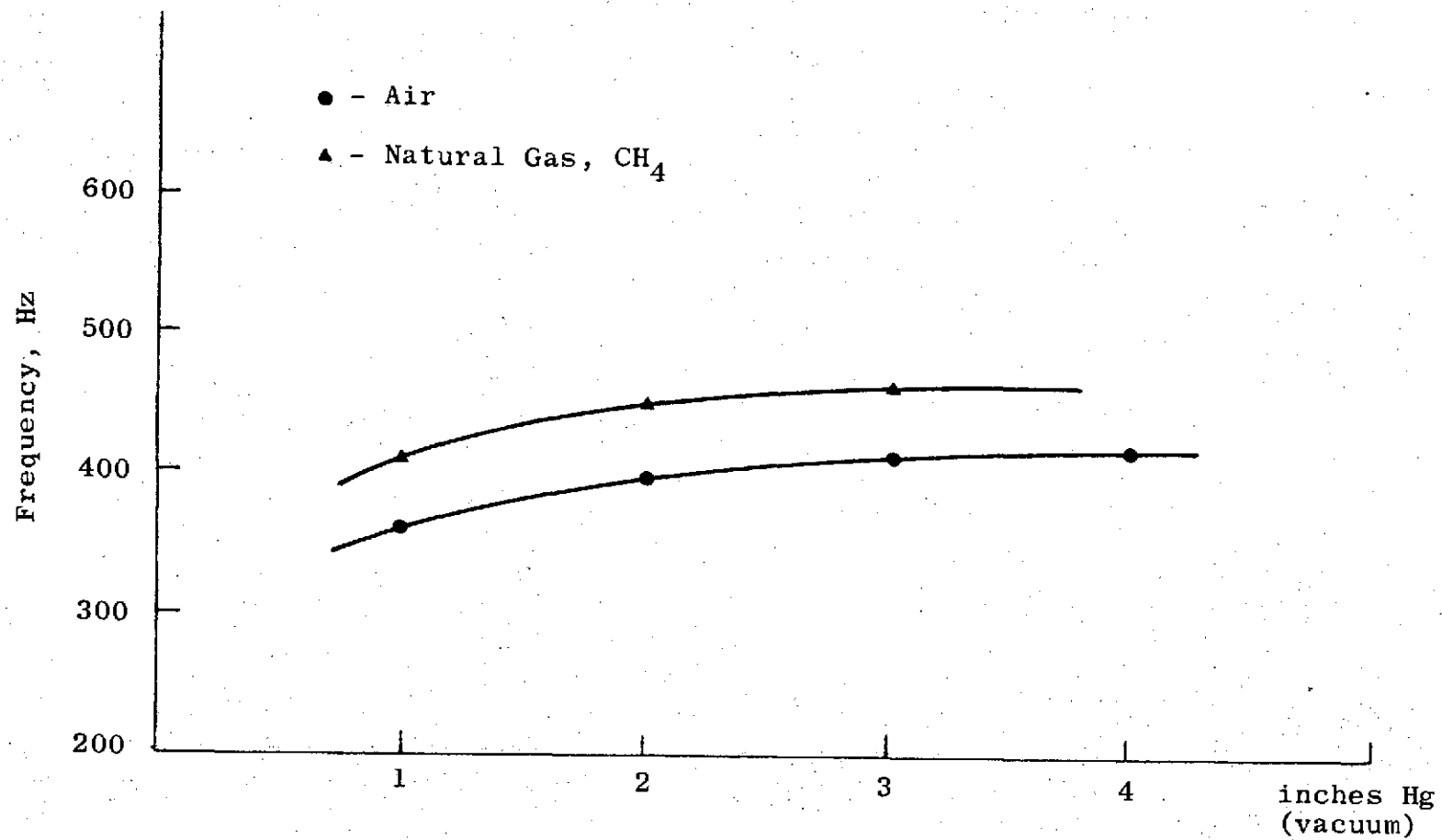
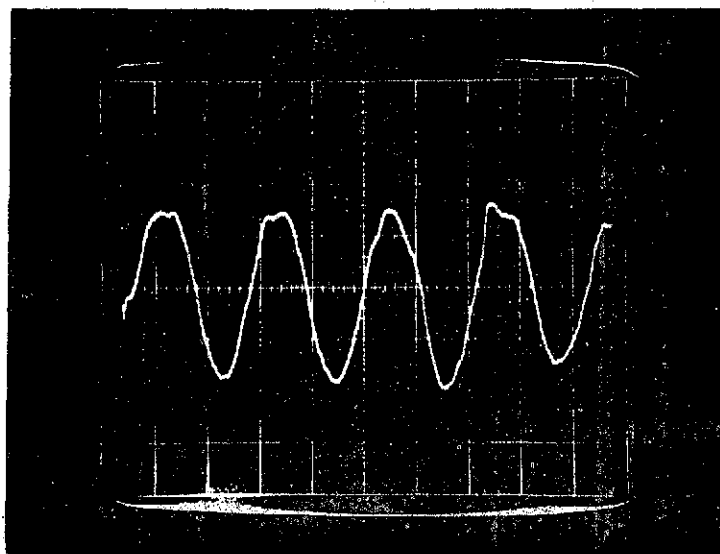
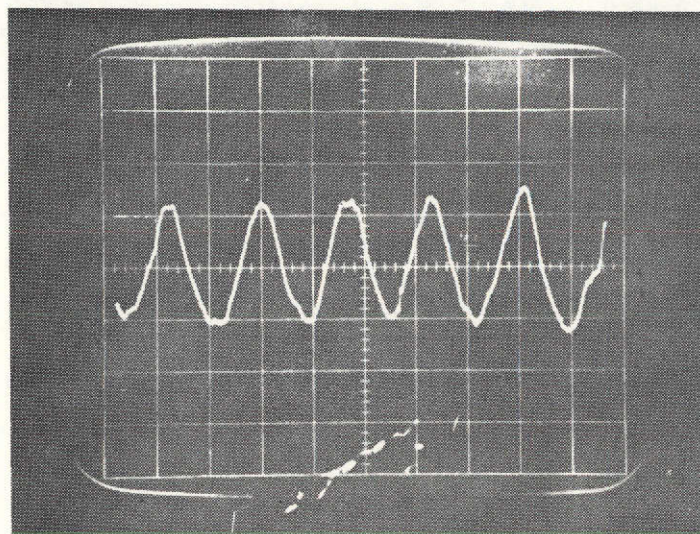


Fig. 14 F-1 Frequency versus Pressure Differential; Air, CH₄

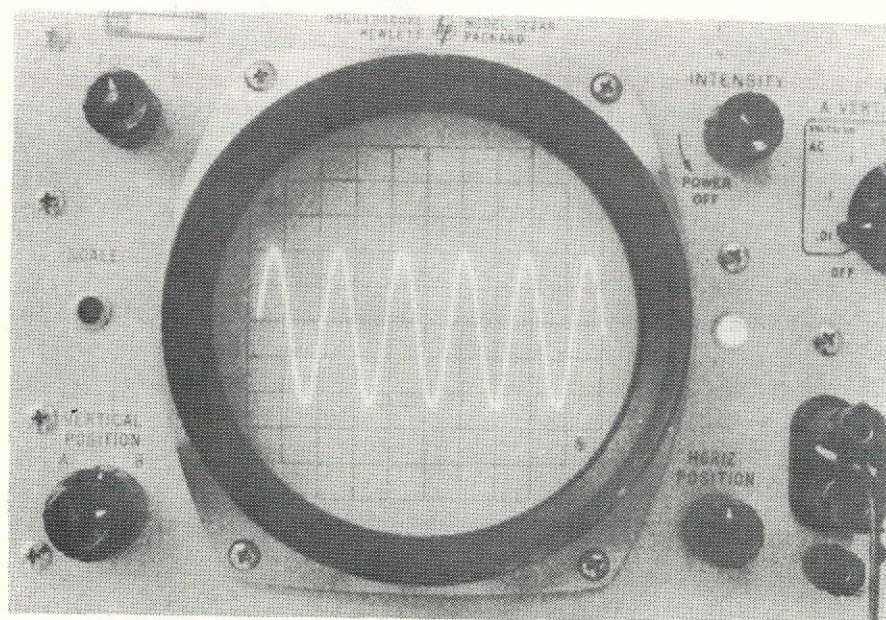


(unfiltered)

Fig. 15 F-2 Signal Trace, Air



(unfiltered)



(filtered)

Fig. 16 F-2 Signal Trace, CH₄

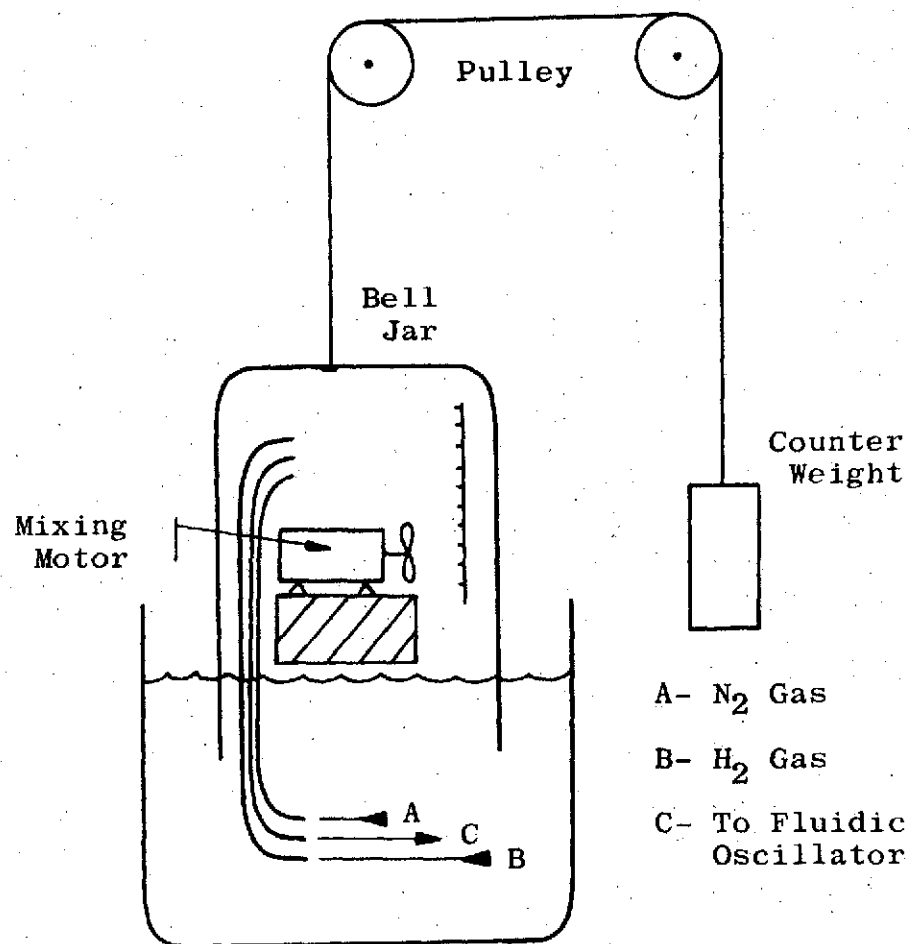


Fig. 17 Positive Displacement Mixing Chamber, Sketch

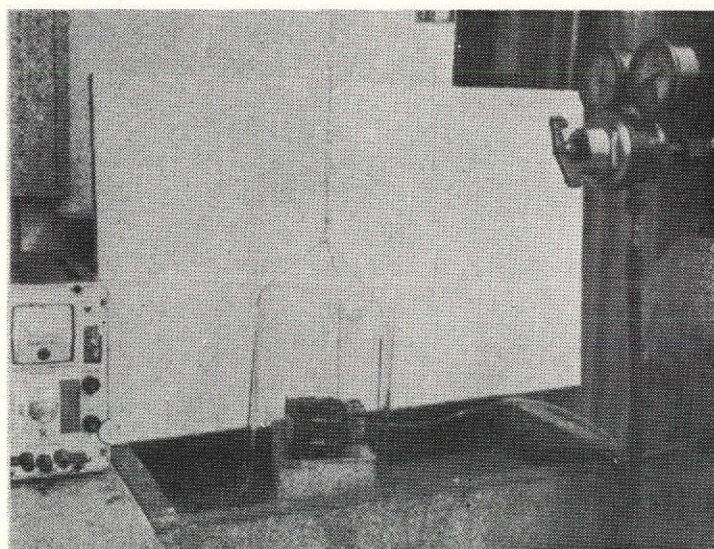


Fig. 18 Positive Displacement Mixing Chamber, Photograph

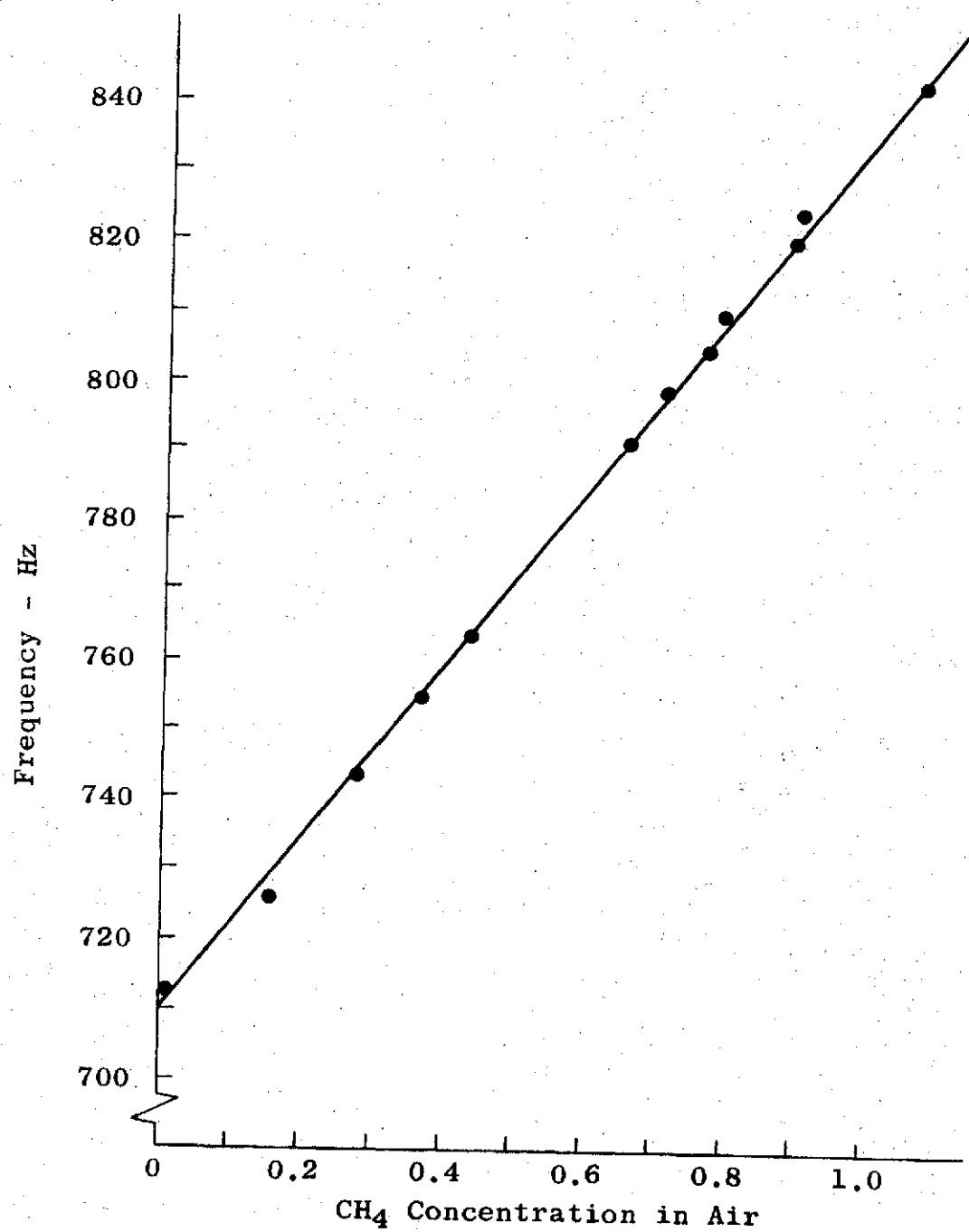


Fig. 19 F-2 Frequency versus CH₄ Concentration in Air

The results to determine the pressure sensitivity of the oscillator to both natural gas and air are shown in Fig. 20.

Flow rate measurements as a function of the pressure differential across the fluidic oscillator are presented in Fig. 21. These curves show that both flow and frequency become asymptotic to some given value as choking of the flow takes place. In other words the oscillator becomes insensitive to further changes in pressure.

Fig. 22 presents the relationship between frequency ratio of a mixture and air versus the velocity of sound in the mixture to that of air. The relationship is linear as would be expected from the theory.

The frequency response of the F-2 fluidic oscillator to various pure gases is given in Fig. 23.

The frequency response to various binary gas mixtures in terms of concentration by volume is presented in Fig. 24 again for the F-2 feedback fluidic oscillator.

A theoretical analysis of the F-2 feedback fluidic oscillator can be made as follows:

The oscillator operating conditions are

$$P_1 = 14.7 \text{ PSIA}$$

$$T_1 = 78^\circ \text{ F}$$

$$[\Delta P]_{\text{EXT}} = 9'' \text{ Hg}$$

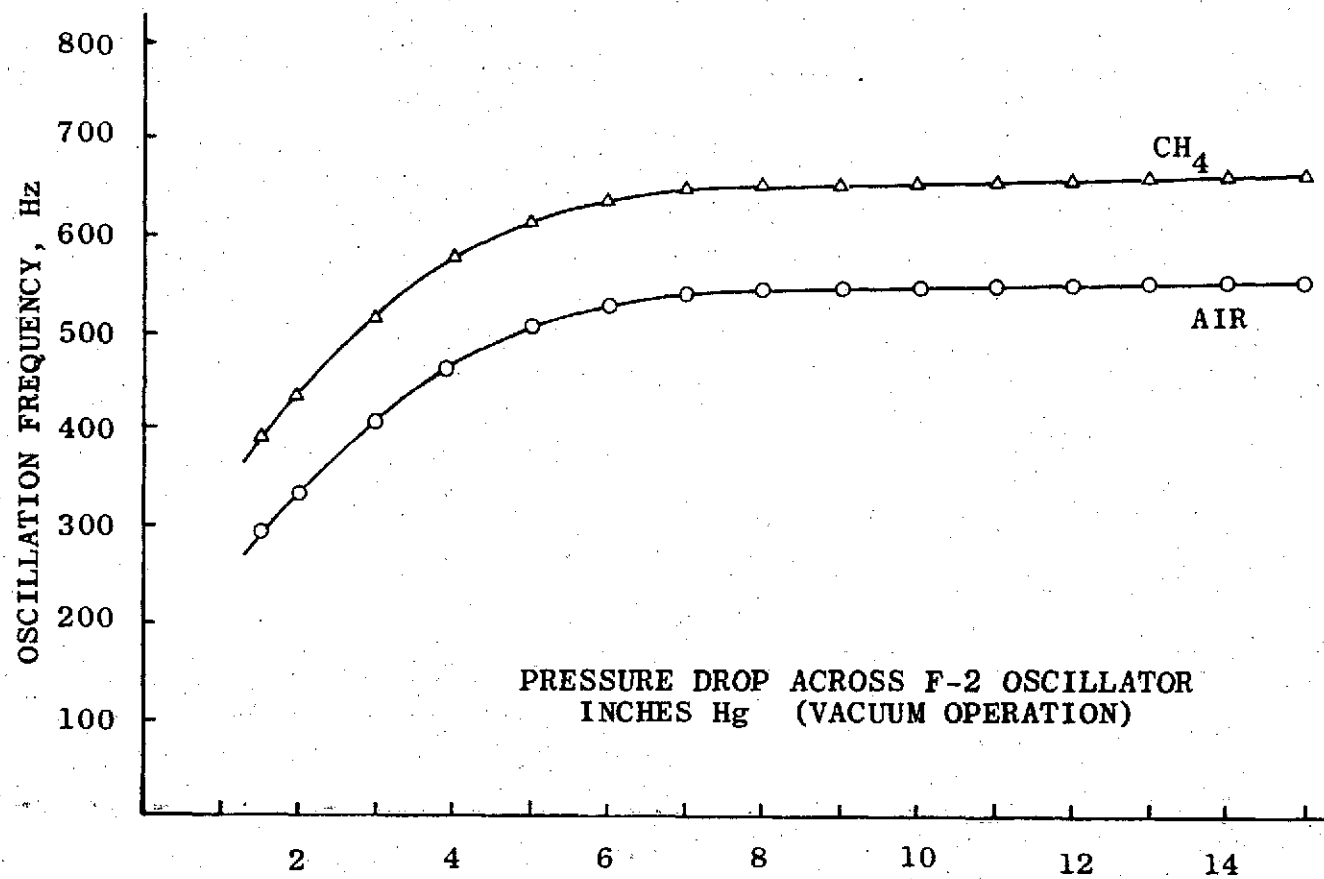


Fig. 20 F-2 Frequency versus Vacuum Differential; Air, CH_4

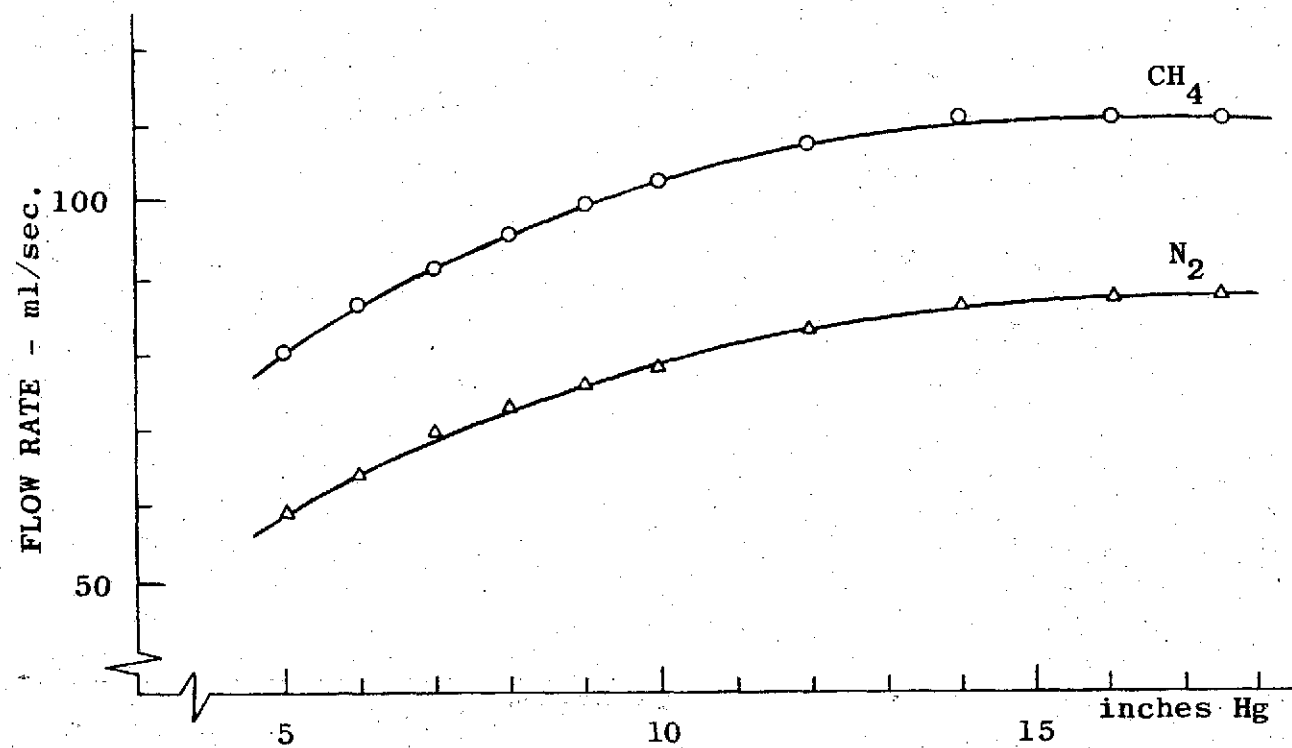


Fig. 21 F-2 Flow Rates versus Pressure Differential

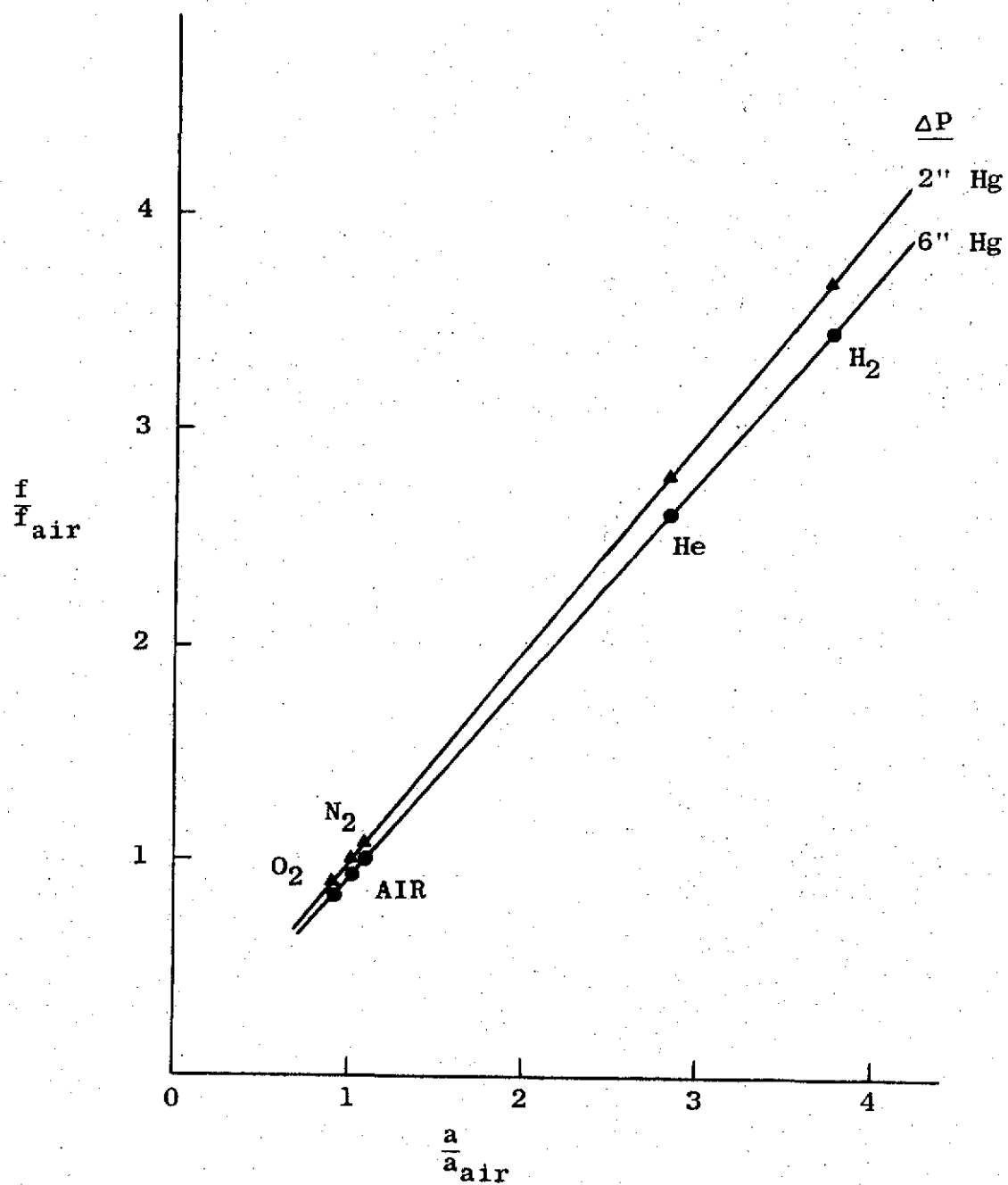


Fig. 22 F-2 Frequency Ratio versus Velocity of Sound Ratio for Different Gases

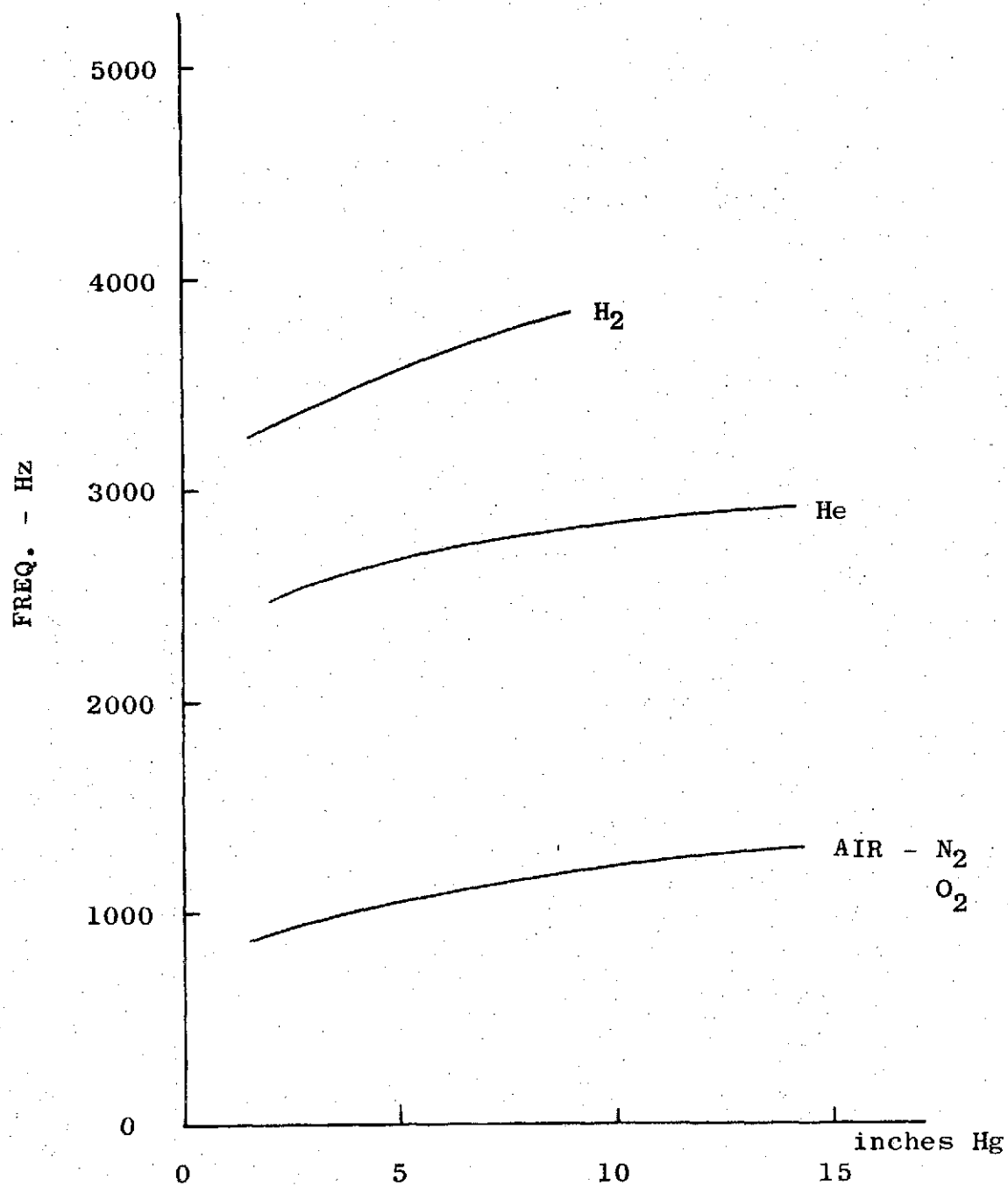


Fig. 23 F-2 Performance Curve for Different Gases,
Frequency versus Pressure Differential

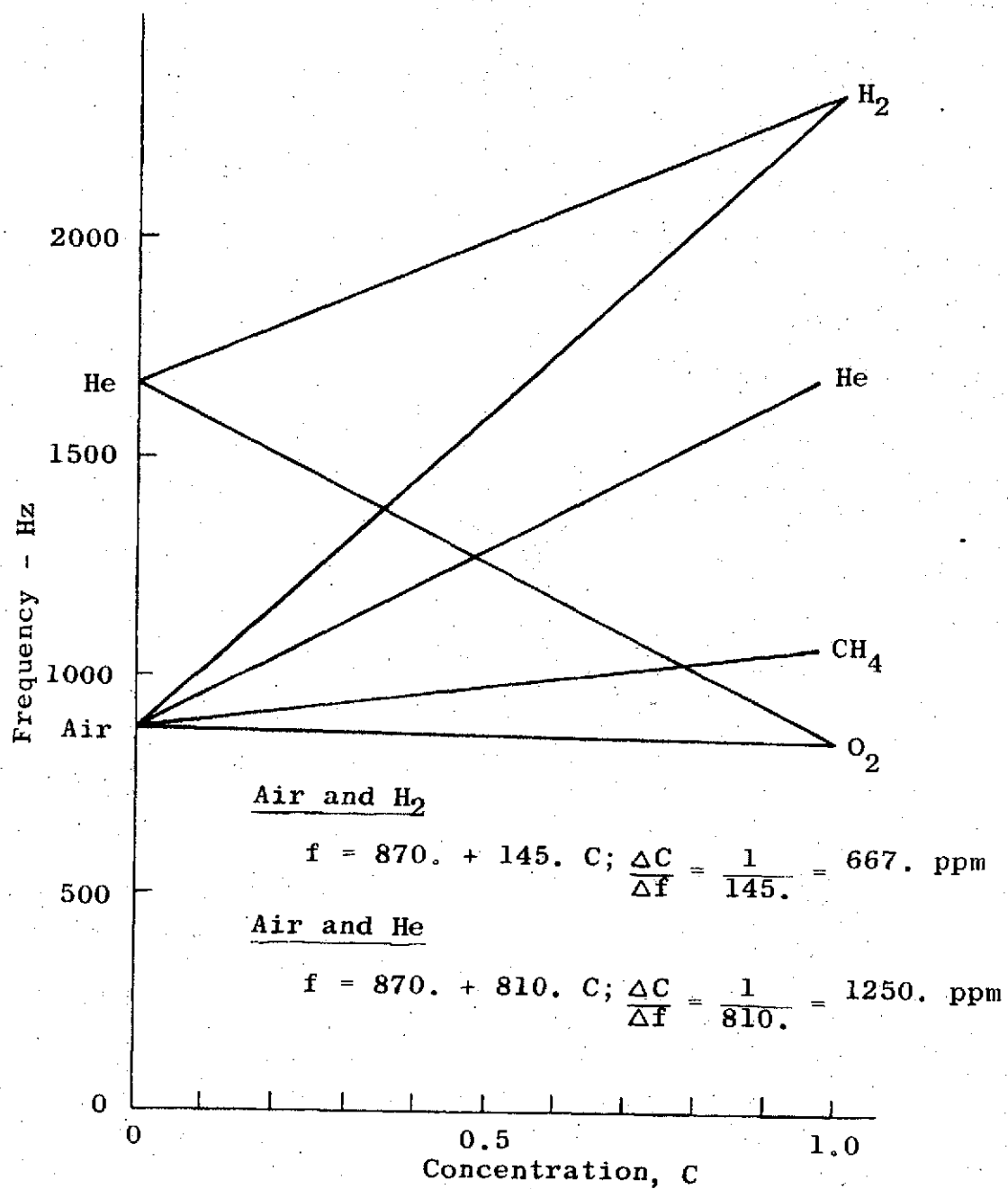


Fig. 24 F-2 Performance Curves

neglecting losses through the exhaust ports (for the first approximation)

using the gas tables for air

$$M = 0.74$$

and the jet velocity

$$\begin{aligned} V_j &= \left(\frac{32.2 \times 1.4 \times 1545 \times 532}{29} \right)^{\frac{1}{2}} \times 0.74 \\ &= 1130 \times 0.74 = 836 \text{ ' / SEC} \end{aligned}$$

From area ratios (neglecting feedback loop losses)

$$\text{Feedback} = 0.50 \quad \text{OR} \quad 50\%$$

Thus the feedback pulse velocity

$$V_{FB} = \frac{836}{2} = 418 \text{ ' / SEC}$$

and the oscillator frequency

$$\begin{aligned} f &= \frac{V_{FB}}{2l} = \frac{418 \times 2.54 \times 12}{2 \times 4.83} \\ &\approx 1320 \text{ ~ / SEC} \end{aligned}$$

Now with the approximate velocity known losses can be estimated

$$\begin{aligned} Re &= \frac{D v l}{\mu} = \frac{0.06 \times 418 \times 3600 \times 0.075}{12 \times 0.044} \\ &= 1.28 \times 10^4 \end{aligned}$$

then the pressure drop can be determined using the friction factor from the Moody chart

$$\begin{aligned}\Delta P &= F \frac{e v^2}{2g} \frac{L}{D} \\ &= 0.023 \frac{0.075 \times 418^2 \times 0.9 \times 12}{2 \times 32.2 \times 12 \times 0.06} \\ &= 7.04 \times 10' = 70.4 \text{ #/ft}^2 \\ &= 0.49 \text{ PSI}\end{aligned}$$

The corrected

$$\begin{aligned}[\Delta P]_{EXT} &= 4.5 - 0.49 \\ &\approx 4\end{aligned}$$

$$P_2 = 14.7 - 4 = 10.7 \text{ PSIA}$$

$$\frac{P_2}{P_1} = \frac{10.7}{14.7} = 0.728$$

$$M = 0.69$$

$$V_j = 1130 (0.69) = 780' / \text{sec}$$

Same procedure as before

$$f = 1320 \frac{780}{836} = \underline{\underline{1230}} \text{ ~/SEC}$$

Further iterations will give more accurate results but even this value agrees remarkably with the measured value, it is within less than 2%. Actually the accuracy of manufacture of the channels can account for more variation than this.

The S series oscillators operate on the same principle as the F series, they however, have been specifically designed to efficiently provide high momentum feedback, and also for the efficient escape of the stagnant gases. Several different sizes and designs of these oscillators have been constructed. Their basic purpose being to increase the sensitivity and maintain the strong signal response of the original F-1 design.

A photograph of the S-4 oscillator (the number referring to the size of the design, the larger the number the smaller the design) is shown in Fig. 25. This flow channel design proved to be optimum and was used in all subsequent oscillator designs. Tying the two exhaust ports together and thus rectifying the signal will give twice the frequency which is observed in each feedback loop. Halving the size of the oscillator will double the frequency of oscillation.

Fig. 26, Fig. 27 and Fig. 28 present the traces of three of the S series type oscillators the S-1, the S-3 and the S-4.

Traces are shown both for air and hydrogen as the working fluid.

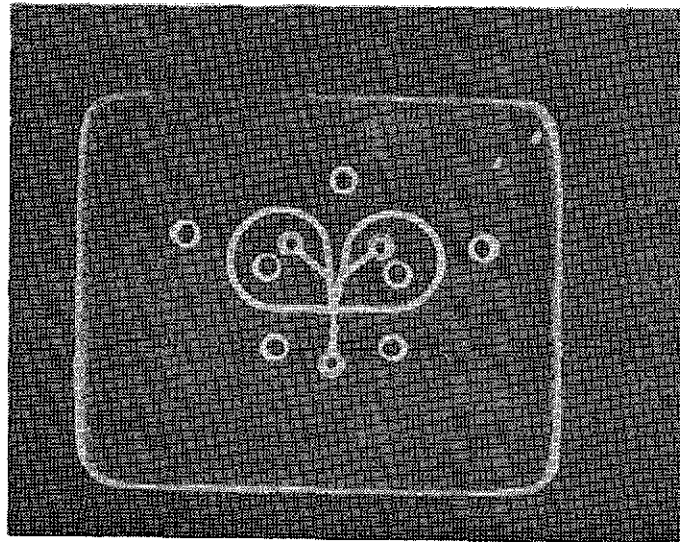


Fig. 25 S-4 Feedback Fluidic Oscillator

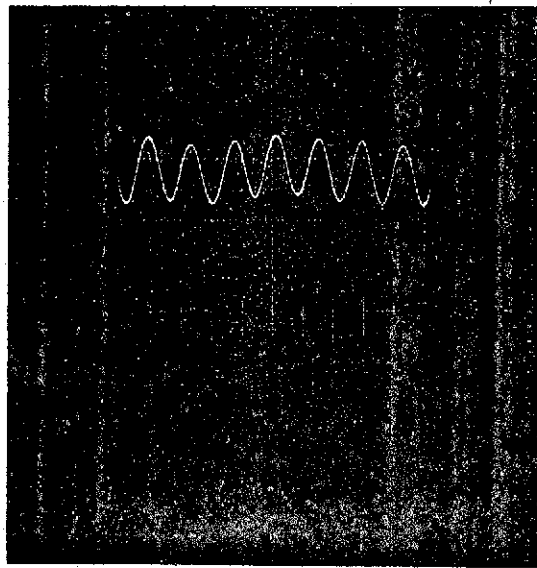


Fig. 26 S-1 Signal Trace, Air.

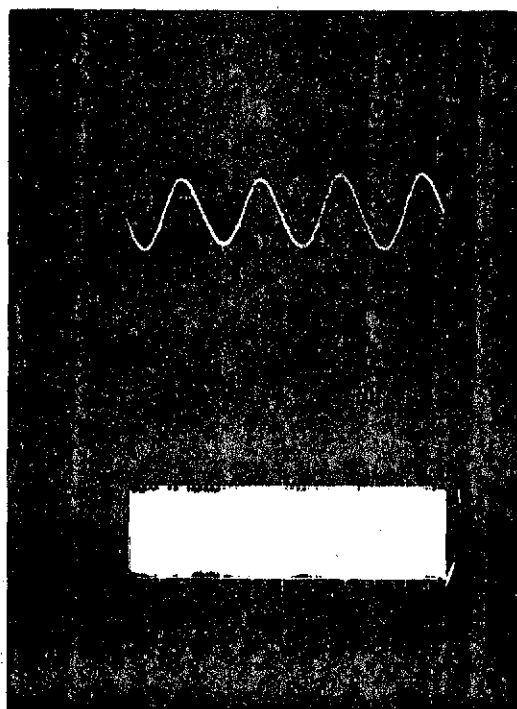
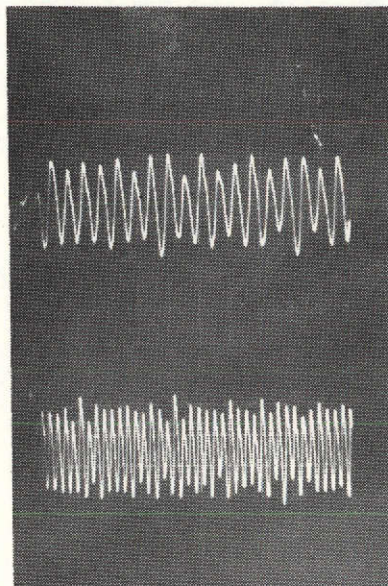
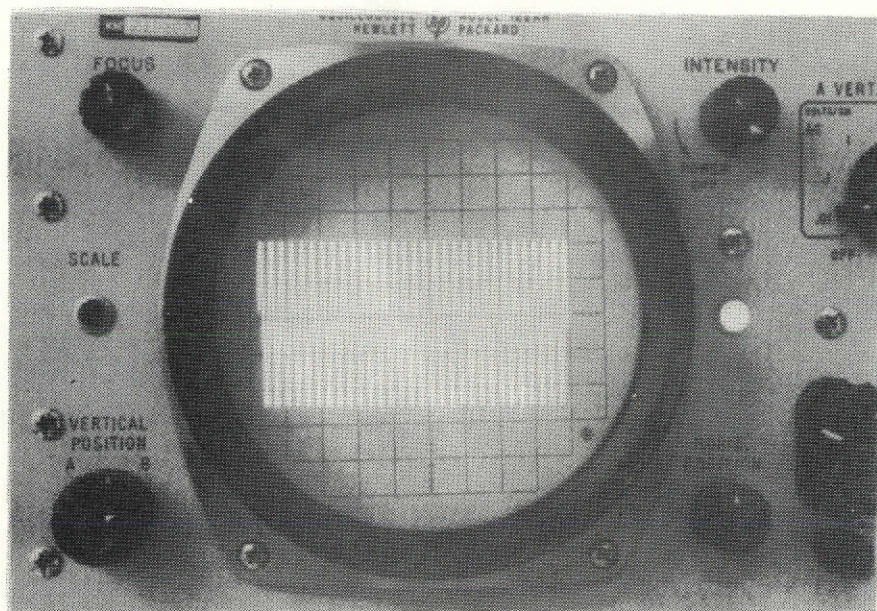


Fig. 27 S-3 Signal Trace; Air, H₂



(unfiltered)



(filtered)

Fig. 28 S-4 Signal Trace; Air, H₂

Frequency variation with pressure curves were obtained and are presented in Fig. 29 with the response of the S-4 and S-6 oscillator (which is half the size of the S-4) to natural gas and air being compared. The frequencies reported are the ones in the feedback loop and would be twice these values in the output line.

The response, as can be seen, is nearly independent of pressure in the case of the S-4 feedback oscillator.

Fig. 30 and Fig. 31 show the S-4 and the S-6 oscillators in the complete assembly and ready to be installed for testing the response characteristics. Some of the S-6 oscillators designed operate with 3 inches of Hg pressure differential and produce a strong 16,000 Hz signal under these (air) conditions. An analysis as shown for the F-1 earlier gives again theoretical frequencies very close to those actually mentioned.

As a result of an analysis of the theory of operation and the experimental results certain general characteristics of the F and S series oscillators can be obtained.

Fig. 32 presents the performance of the S-6 fluidic feedback oscillator in terms of gas concentrations of binary mixtures using the unrectified frequency as the basis for plotting.

The S-6 oscillator which was used for the field tests for monitoring the H₂ cloud during the auto-ignition boil-off experiments operated in air at the base frequency of slightly over 16,000 Hz which corresponds to a sensitivity of ± 30 ppm. per cycle at the fundamental frequency and will be increased to lower ppm values with increase in the frequency.

Since some interference was observed during the field tests a filter circuit was designed and Fig. 33 shows both the unfiltered and

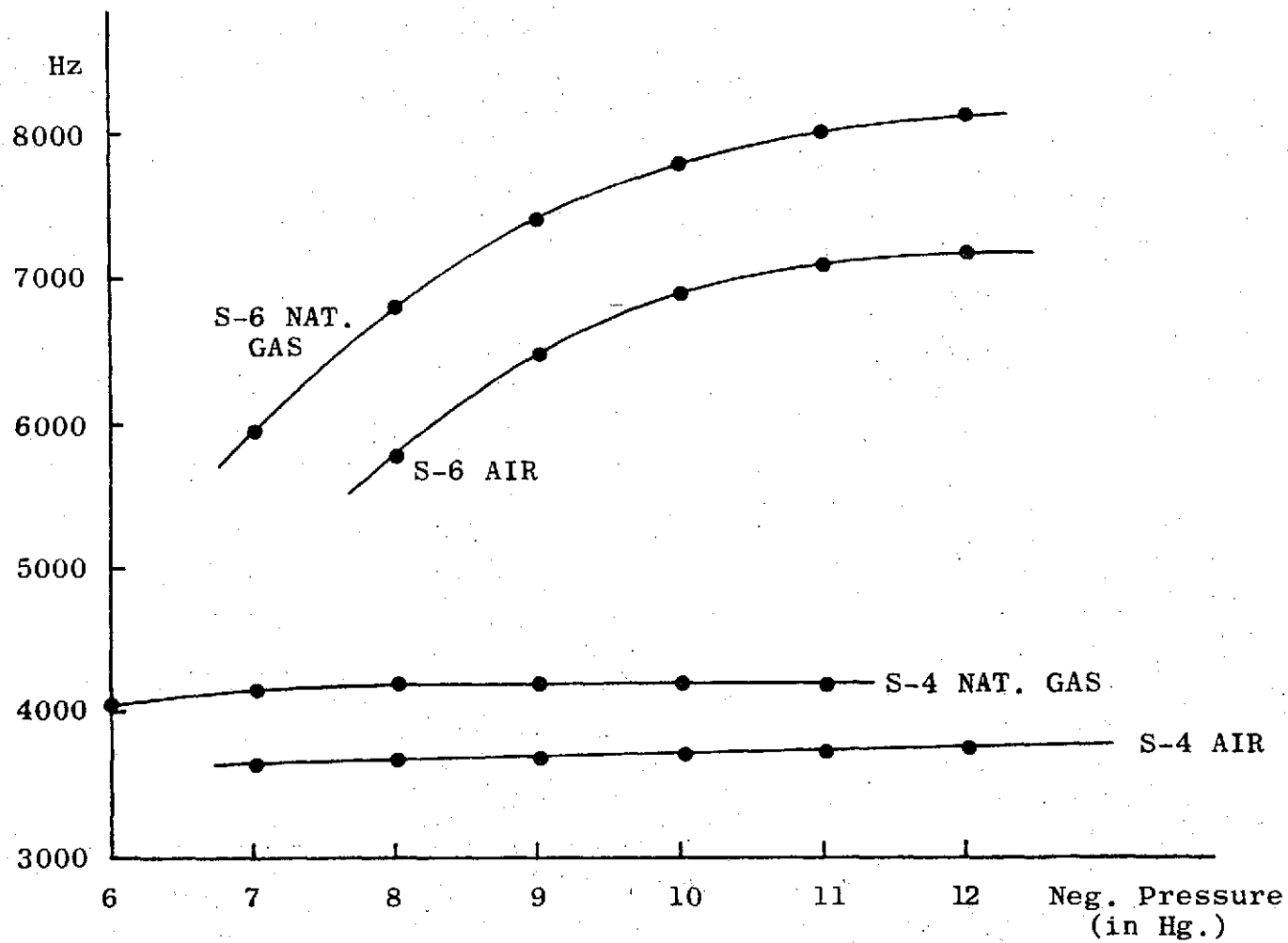


Fig. 29 S-4, S-6 Performance, Frequency versus Pressure Differential

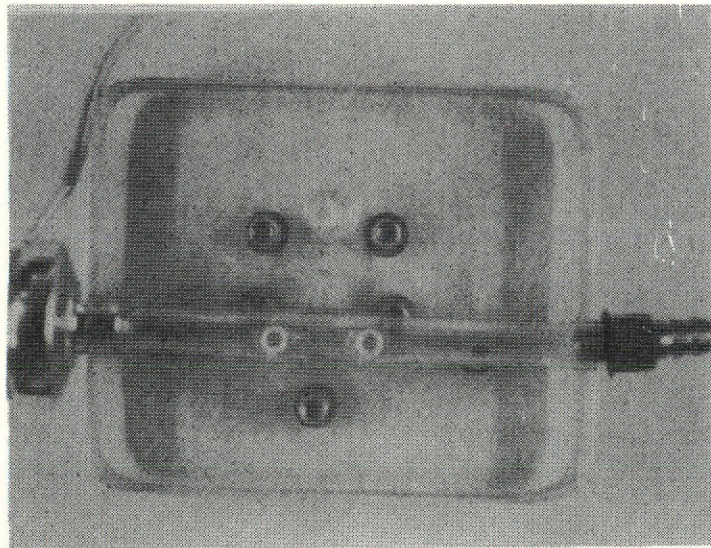


Fig. 30 Complete S-4 Feedback Oscillator

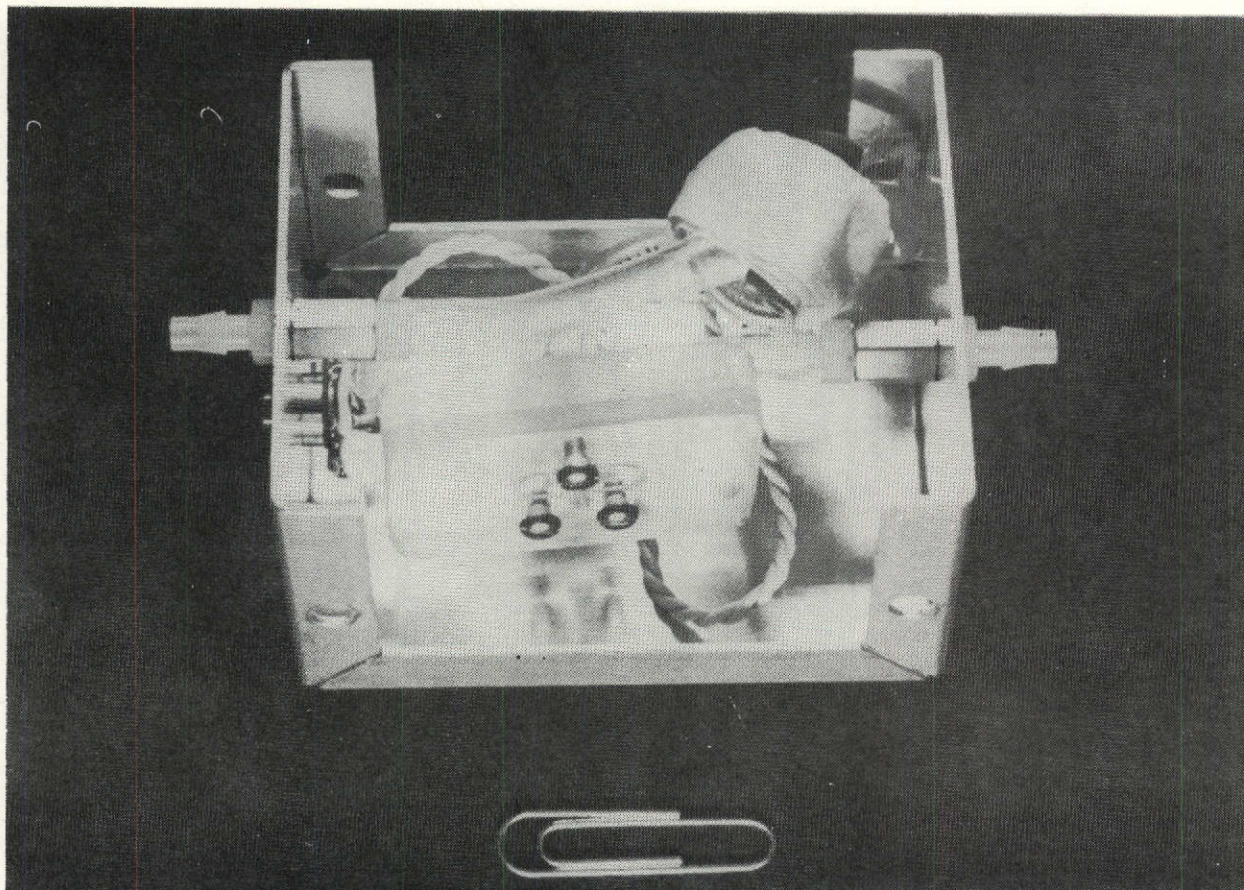


Fig. 31 Complete S-6 Feedback Oscillator

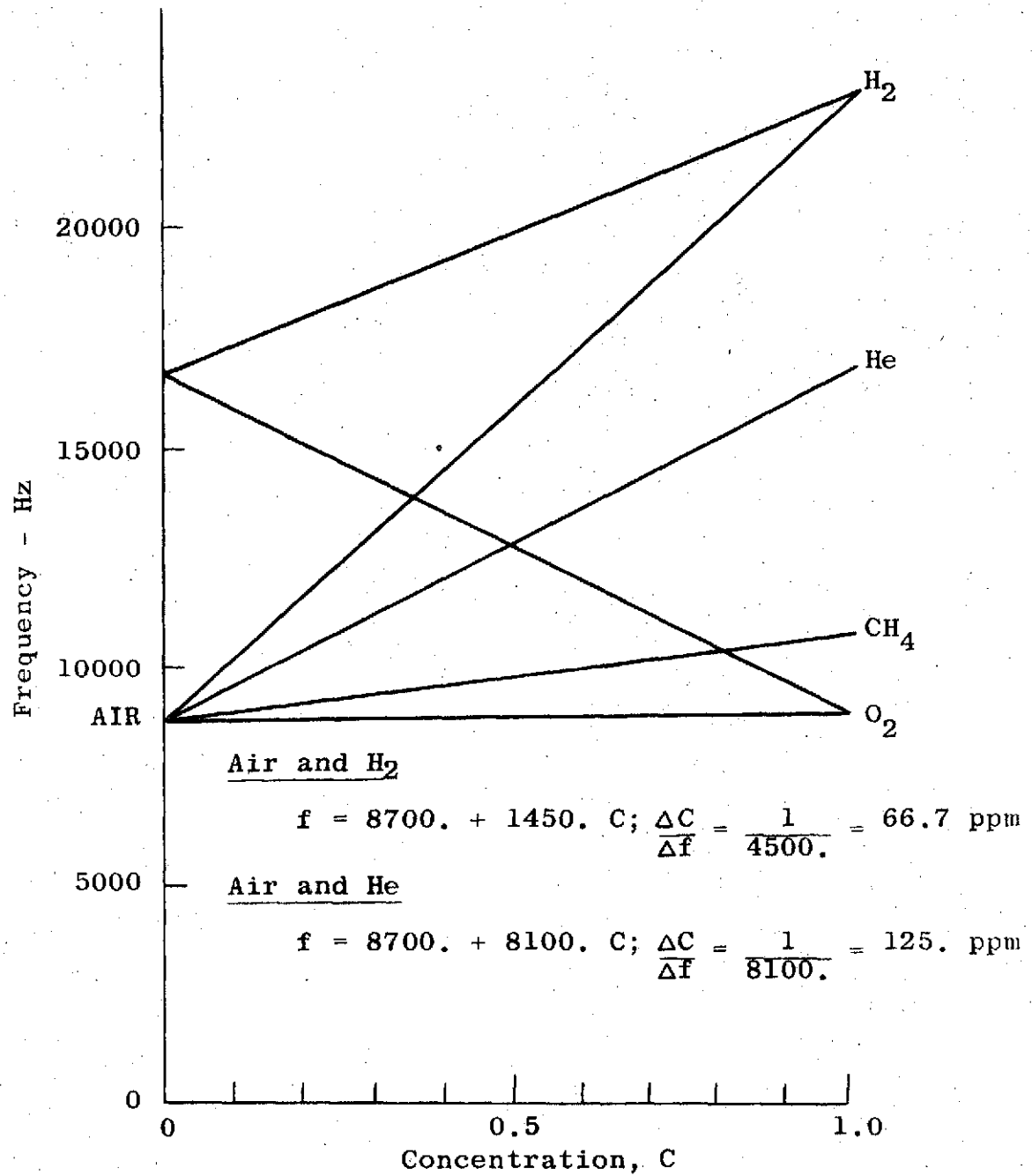


Fig. 32 S-6 Fluidic Oscillator Performance

the filtered signal trace of the S-6 fluidic feedback oscillator.

Summary of General Properties and Characteristics of the F and S series fluidic feedback oscillators.

These type fluidic devices are essentially digital or proportional amplifiers with feedback loops. An analysis leads to the following results.

Size: Reducing the size of the oscillator to one half will in general double the frequency.

Oscillation frequency: The frequency of oscillation can be monitored by transducers and will translate pressure pulses at the exhaust ports into electrical signals. This is the fundamental oscillator frequency. If the exhaust ports are tied together the signal from the oscillator is rectified and twice as many pulses are felt by the transducer thus doubling the frequency.

Channel Depth Increase: (Aspect Ratio):

1. Increases the flow
2. At aspect ratios of less than about four the effect of boundary walls increases.
3. Other characteristics are unaffected.

Control Nozzle Area Increase:

1. Decreases control pressure necessary for switching.
2. Increases the effect of open controls.
3. Increases tendency to oscillate.

Interaction Region Width Increase:

1. Increases control flow necessary for switching (up to set-back of 2 w)
2. Increases power jet pressure at which the jet attaches to both boundary walls.

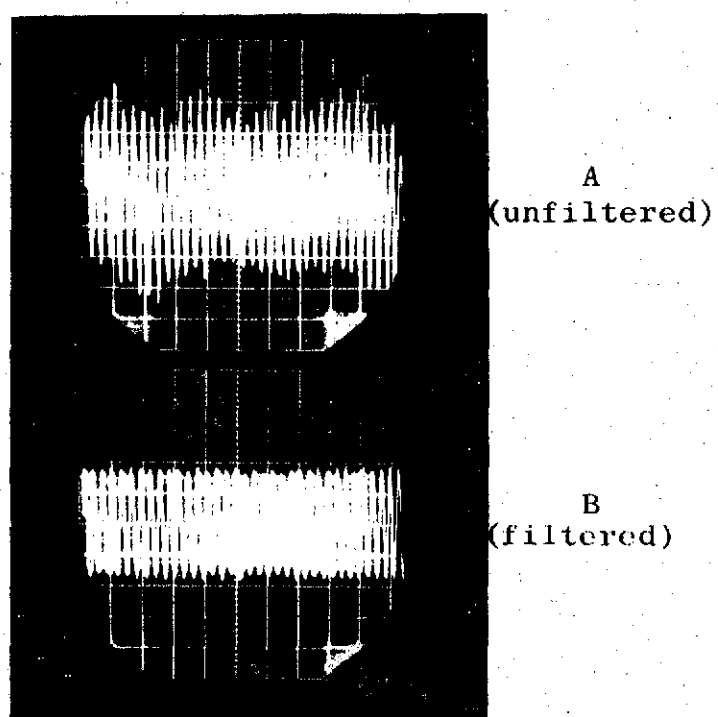


Fig. 33 S-6 Signal Traces

Receiver Aperture Increase:

1. Increases counterflow
2. Decreases pressure recovery

Boundary Wall Angle Increase:

1. Decreases flow for switching
2. Moves the stream attachment point downstream.

Moving Splitter Downstream

1. Increases counterflow
2. Decreases output energy
3. Decreases pressure recovery
4. Decreases tendency to oscillate

Power Jet Pressure Increase

1. Stream attachment point moves downstream
2. Decreases control pressure
3. Control flow necessary to switching decreases as percent of power jet flow.

Load Increase

1. Increases tendency to oscillate
2. Reduces control flow necessary for switching out of load.
3. Increases control flow necessary to switch into load.

Edgetone Fluidic Oscillators

Parallel to the development of the feedback fluidic oscillator the edgetone type oscillators were investigated and a number designed for the purpose of gas detection.

With two symmetrical cavities placed at each side of the main jet coupling occurs between the jet edge frequency and the cavity resonance frequency which produces continuous oscillations.

With resistance of the passages or cavities negligible the wave propagation velocity from equation (23) becomes equal to the velocity of sound.

The frequency at which the impedance becomes zero determines the natural frequency of the cavity, thus

$$f = \frac{a}{4l}$$

Since the effective total passage length l is 0.35 inches in one of the designs studied the calculated frequency of oscillations should be 9428 hz. This agrees very well with test results. To operate the oscillator the internal pressure must be increased to obtain flow. For the oscillator here this requires approximately 7 inches of water which will increase the frequency of oscillation to 10,548 cps. This value agrees within 148 cps or 1.5% of the experimentally arrived value.

The oscillators of this type are designated as the M series and the experimentally derived properties of these edgetone fluidic oscillators are described on the following page.

Edgetone Fluidic Oscillator Properties (M series):

The M series oscillators are typical edgetone fluidic oscillators, and if designed properly they can be built rapidly and inexpensively without compromising accuracy. One such oscillator is shown in Fig. 34. The oscillator can be made simply by drilling three holes into a piece of plastic or metal and inserting a brass (or other material) tube which has been cut as shown.

The picture in Fig. 35 shows the complete assembly. If the large open parts of the oscillator are covered with cover plates of some impervious material, the oscillator will begin to oscillate if a differential pressure of approximately 7 inches of water is imposed across the brass tube.

The oscillator made according to the dimensions shown in Fig. 34 will generally oscillate anywhere from 10,000 to 12,000 Hz in air. The variation in the frequency of oscillation is primarily due to the variation of the pressure and density in the large Helmholtz cavities. This can easily be observed if one views Fig. 36 where the variation in oscillation frequency with pressure is shown to be 160 cycles per inch of water.

Fig. 37 gives the results obtained from a performance test of a typical edgetone fluidic oscillator of the M series. Some tests were performed using a pressure source of pure nitrogen which was throttled down to operating pressures and the others using a vacuum pump. Each of the experiments was carried out at room temperature to determine the variation in frequency with pressure, the amplitude variation and the variation in frequency of oscillation at a given pressure due to random effects.

All tolerances $\pm .005$ except outside dimension
 $\pm .02$ or as indicated

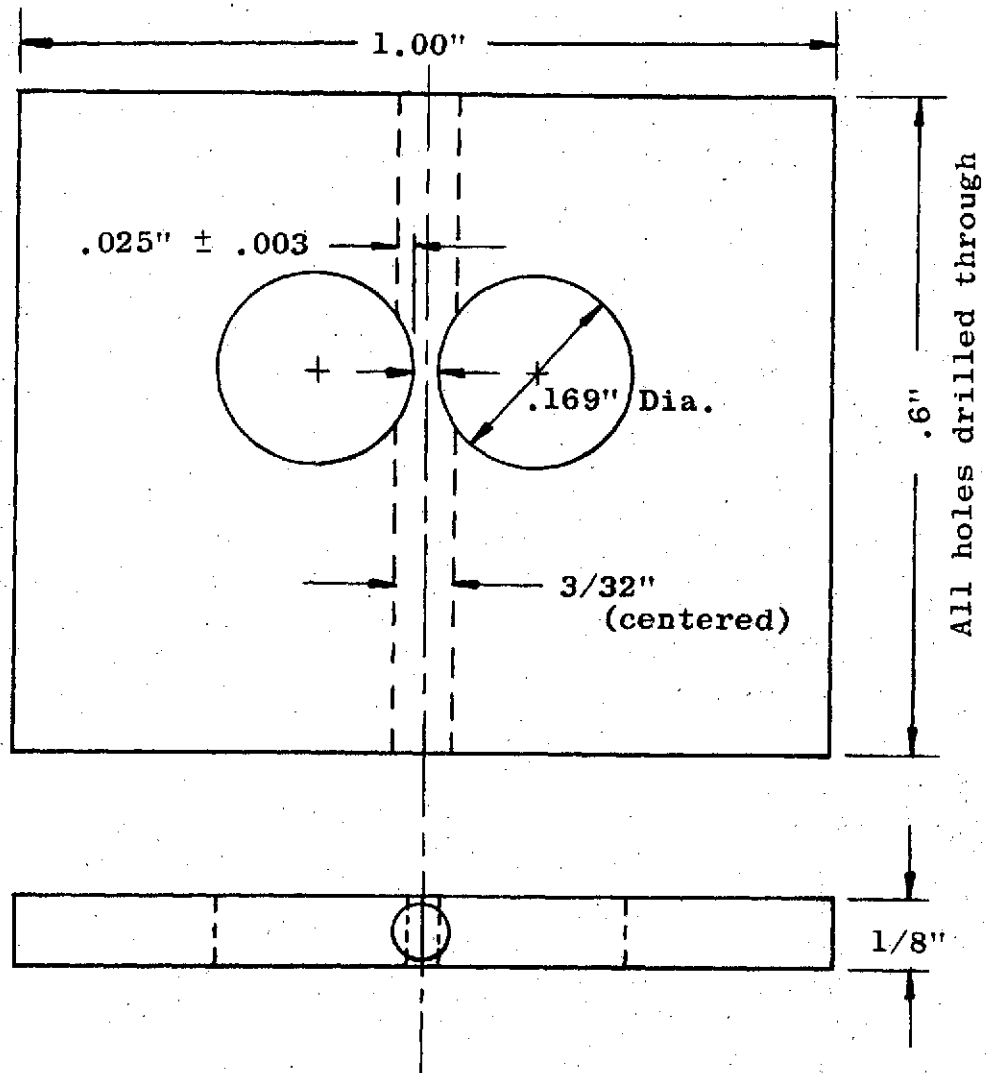


Fig. 34 Edgetone Oscillator Sketch

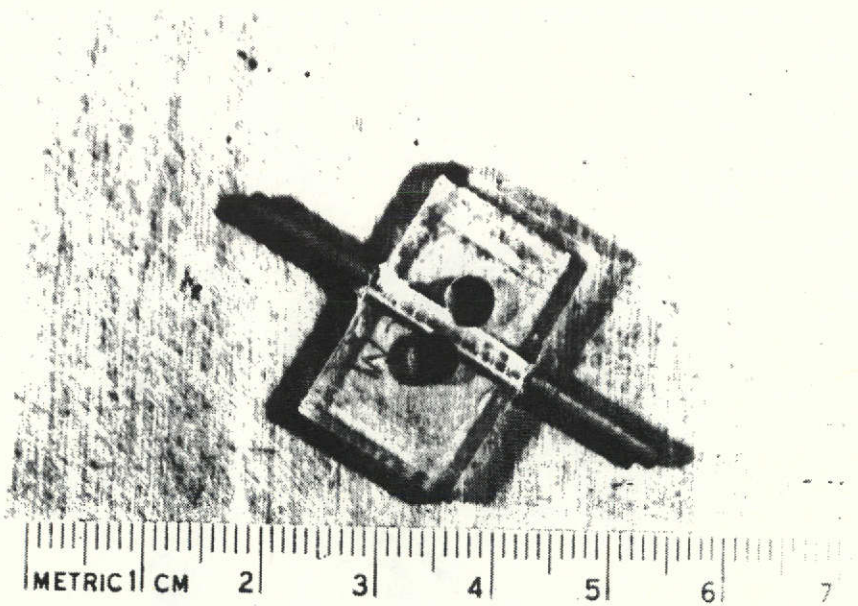


Fig. 35 Edgetone Oscillator Photograph

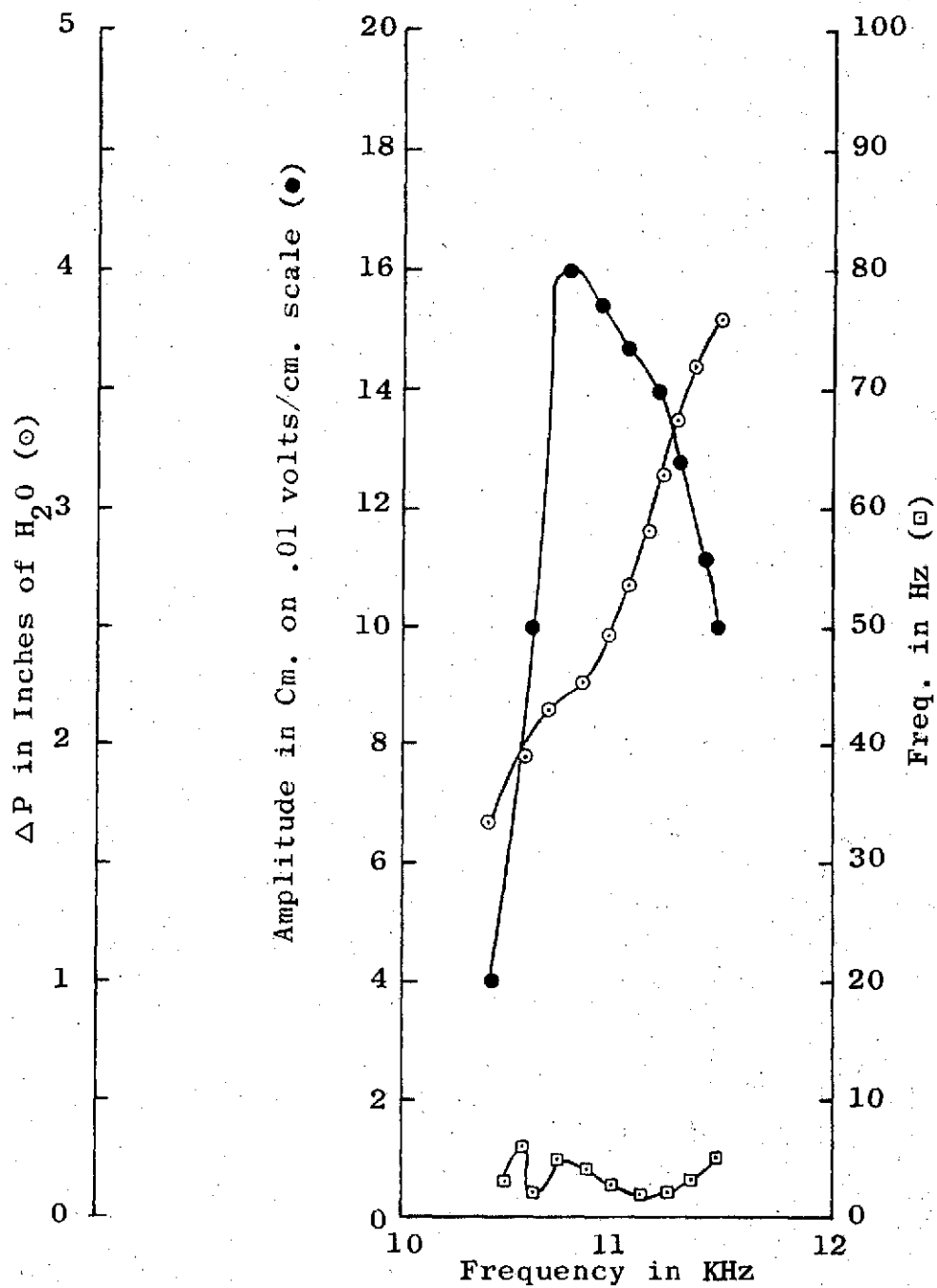


Fig. 36 M-3 Amplitude versus Frequency

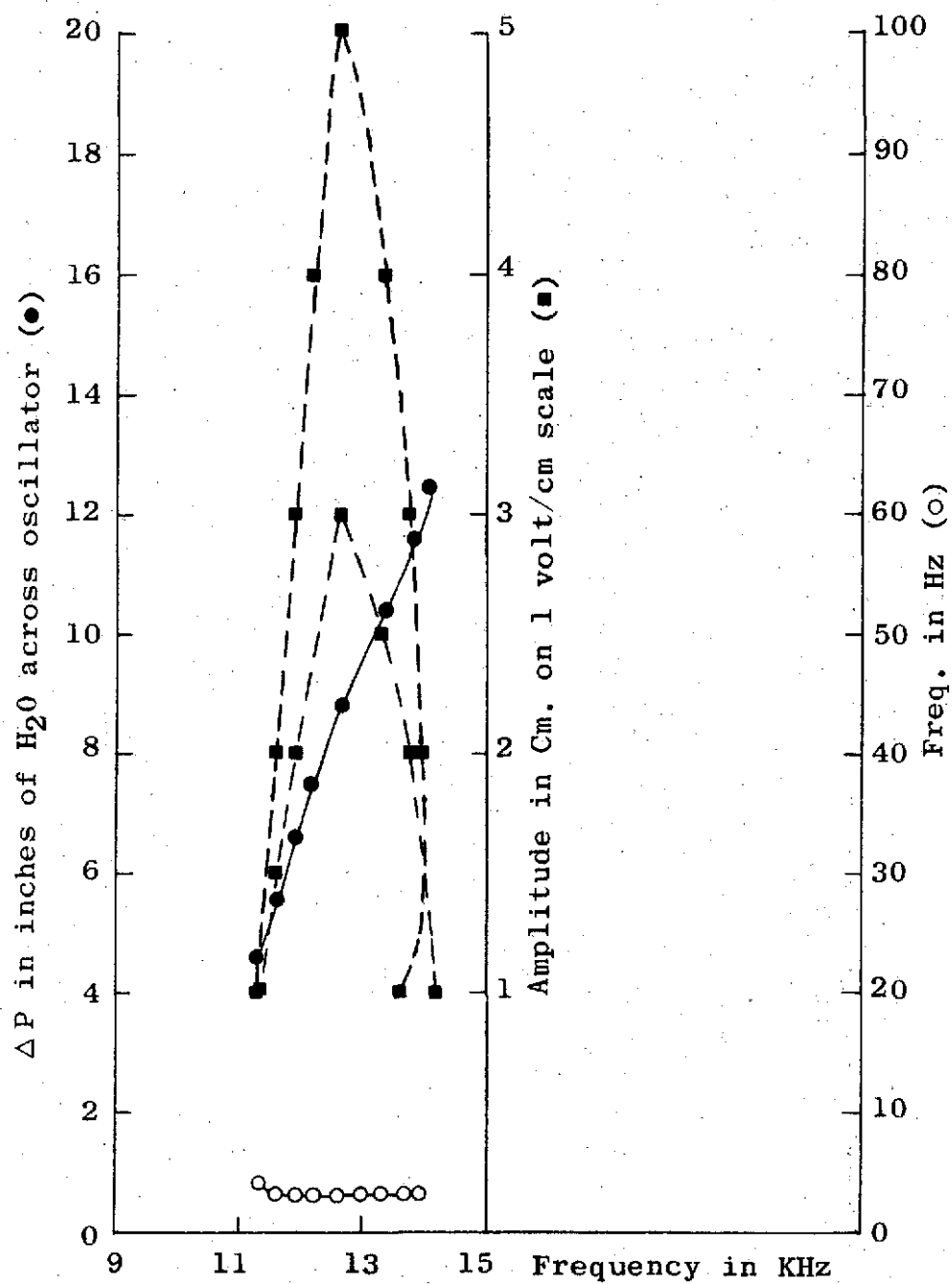


Fig. 37 M-5 Amplitude and Pressure Differential versus Frequency

It should be noted that most oscillators of this type only oscillate between 7 and 15 inches of water, generating the maximum signal at about 9 inches of water.

The pressure tolerance to amplitude appear quite satisfactory and the only requirement for satisfactory operation will be the maintenance of constant pressure. Since the density is pressure dependent measurements should be made at constant pressure to determine density variations due to changes in concentration. Although the output signal in these tests showed an average variation of three cycles per second, under constant conditions, the non-permanent nature of the test set-up contributed to this value. The experimental apparatus will be discussed later. Changes such as using one size tubing, reducing the number of valves in the line, making all connections rigid reduced the system variation to plus or minus one cycle per second.

Fig. 38 shows that the pressure response may be varied as desired with the M oscillator in order to change its sensitivity. The figure shows that if the pressure level is increased in the oscillator to several inches of mercury the sensitivity can be dropped to as low as 31 cps per inch of water.

Fig. 39 and Fig. 40 show the response of the M series oscillator, at room temperature, to varying concentrations of hydrogen and helium in nitrogen. The graphs show that the sensitivity of the oscillator to helium is 35 ppm/cycle and for that of hydrogen is 25 ppm/cycle.

The trace of the output of the M-5 oscillator displayed on an oscilloscope when measuring pure hydrogen is shown in Fig. 41. The M-3 edgetone fluidic oscillator operating on air and natural gas is displayed again as a trace on an oscilloscope in Fig. 42.

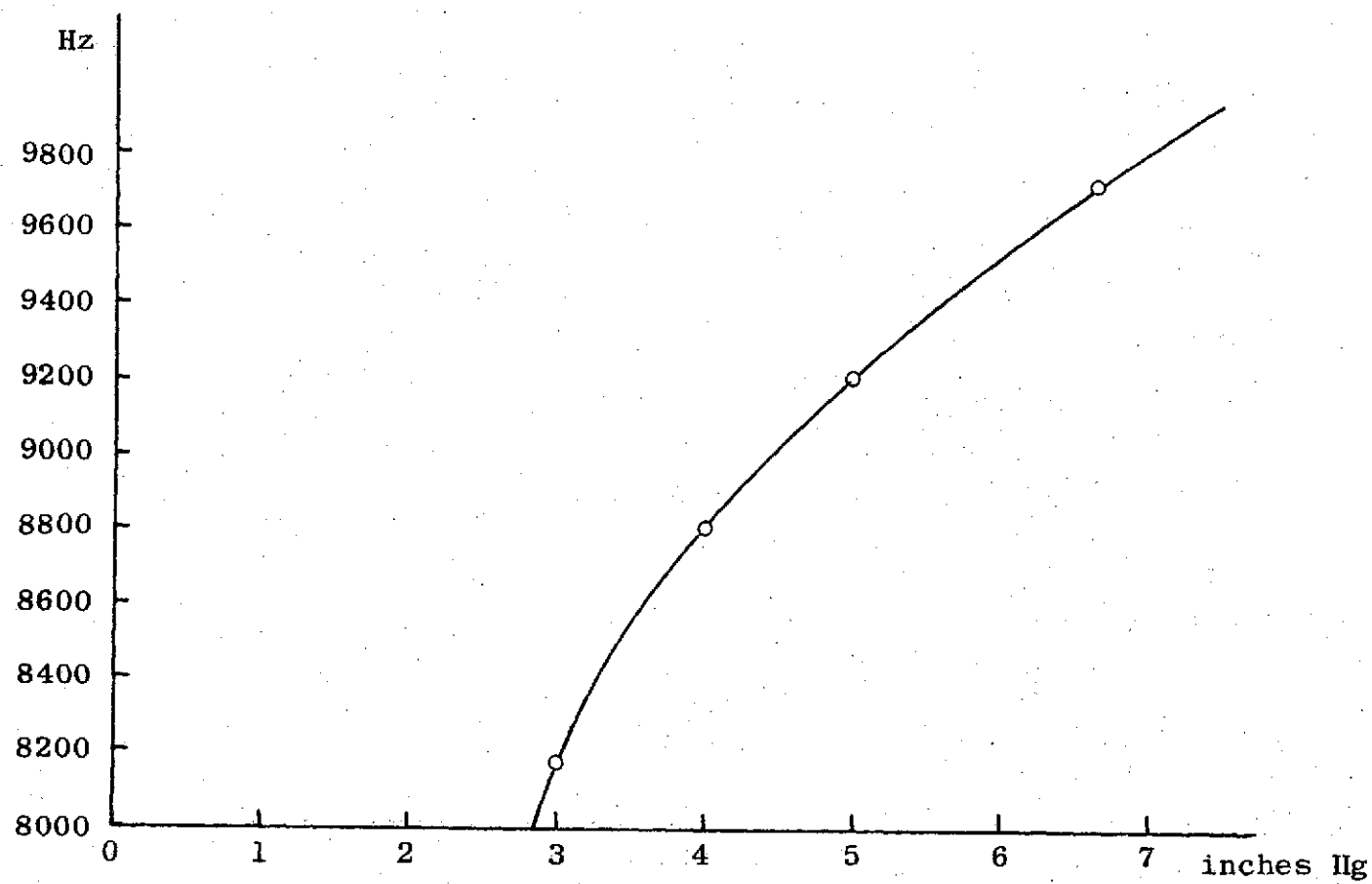


Fig. 38 Frequency versus Pressure Differential

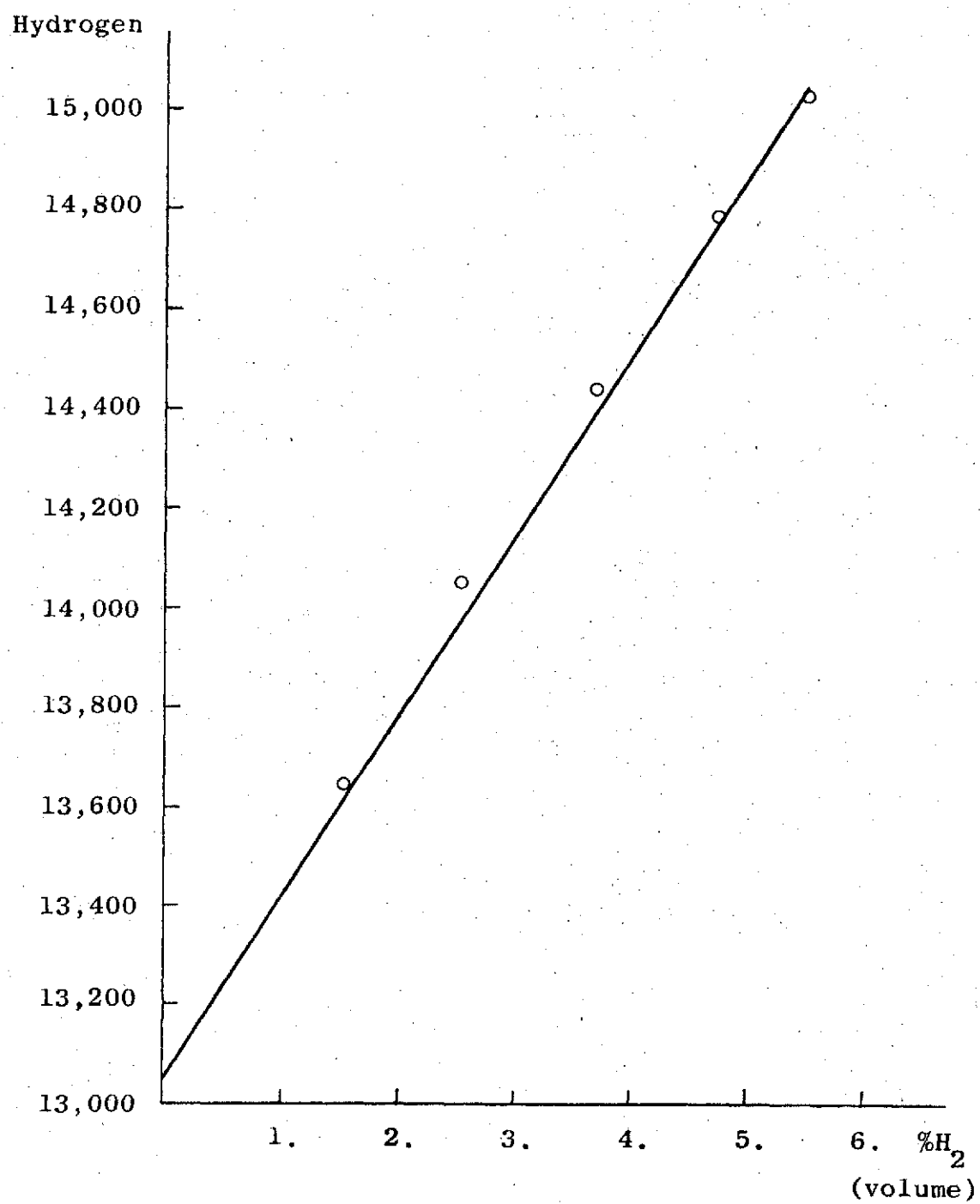


Fig. 39 M-5 Frequency versus H_2 Concentration in N_2

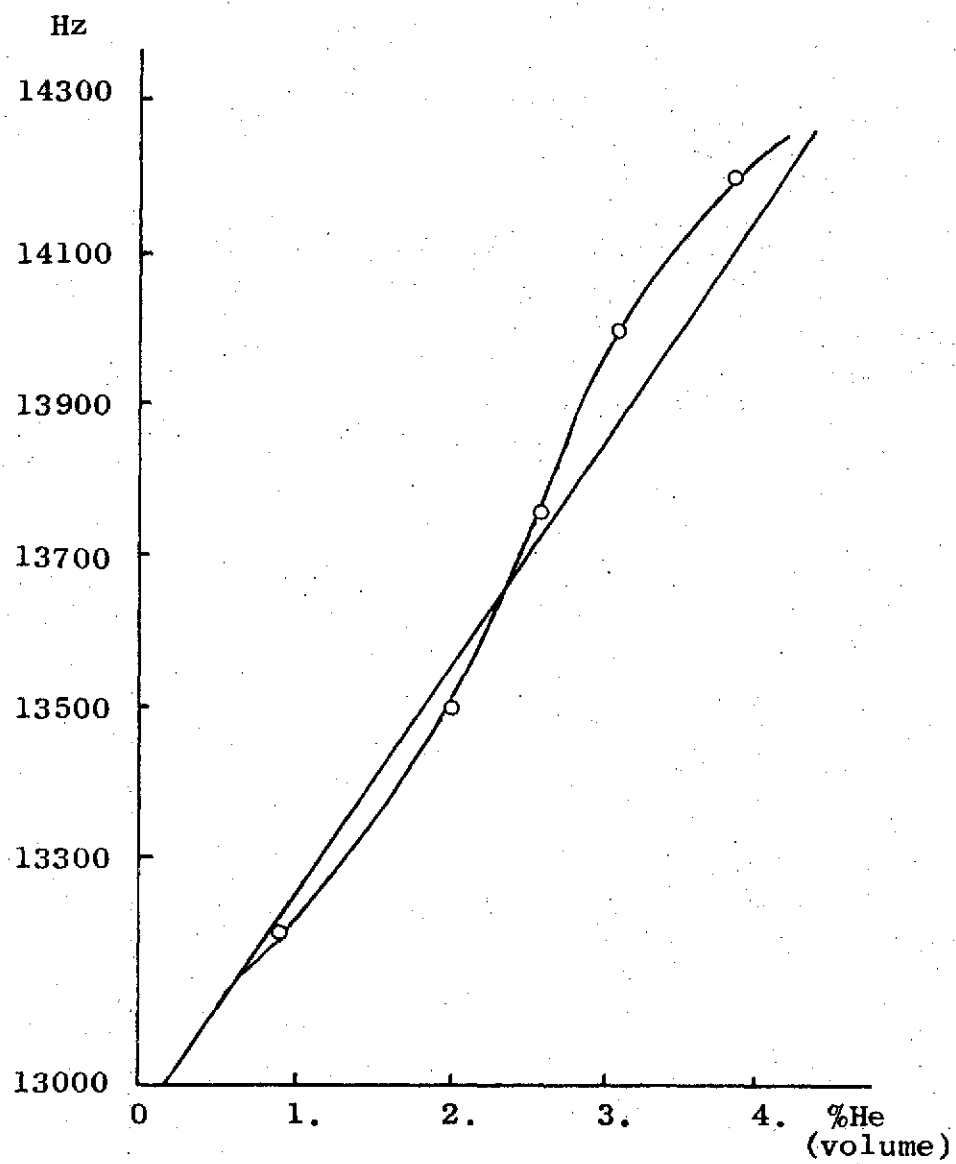


Fig. 40 M-5 Frequency versus He Concentration in N₂

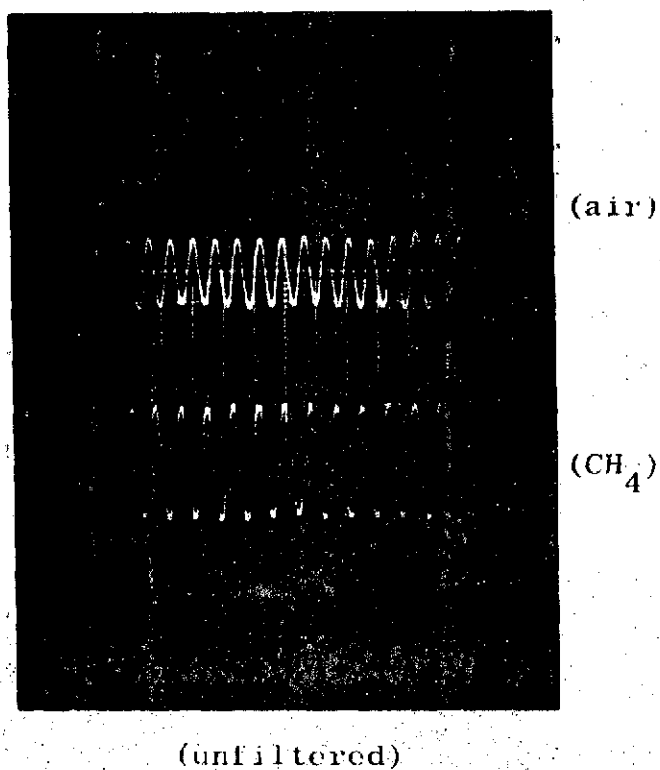
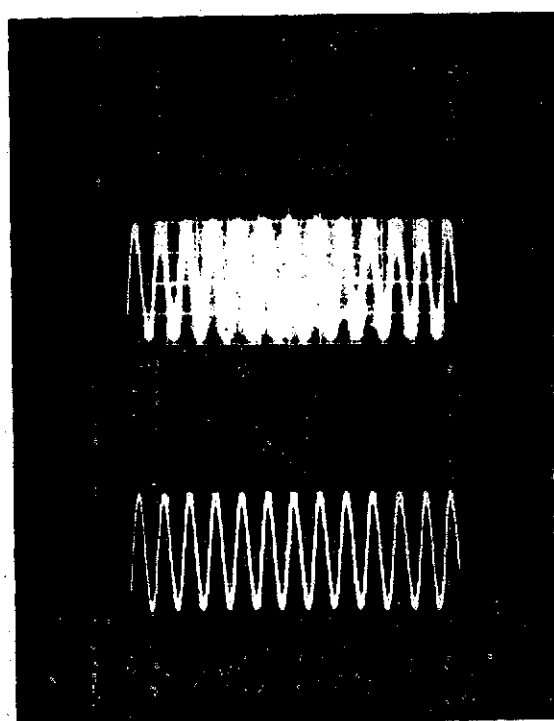


Fig. 41 M-5 Signal Trace, Air, CH₄



(unfiltered)

Fig. 42 M-5 Signal Trace, H_2

ENERGY SOURCES FOR FLUIDIC OSCILLATOR OPERATION

Introduction

At the beginning of this study the directions were not to worry about the source to operate the fluidic oscillators. Whatever was needed would be made available.

Later in the study, however, after the fluidic oscillators were designed and evaluated and confidence had been gained in the ability to give them the desired characteristics, attention was paid to the source or sources which might operate these gas sensors.

Vacuum

The simplest source for operating the gas sensor or fluidic oscillator is a vacuum line to which the oscillator can be connected. In this manner the gas to be sampled is drawn through the sensor which in turn responds to gas density changes with changes in oscillation frequency. Since these sensors can be made with very small ports and channels they do not require much flow through them and will operate with little pressure differential across them.

Compressed Air

Since the gas to be sampled must be drawn through the sensor a vacuum must be provided for its operation. This can be done by letting compressed air expand through a nozzle, or venturi, or ejector (aspirator) which in turn can produce the vacuum required to operate the fluidic oscillator.

Compressed Gas

A compressed gas source such as Nitrogen, Helium, etc. can be used instead of air if available and advantageous and again nozzles, venturies or ejectors can be used to provide the required vacuum for the sensor operation.

Gas Compressor

Under certain conditions it may be advantageous to compress the gas to be sampled and then let it expand to the atmosphere or to an available vacuum through the gas sensor. In other instances the gas to be sampled may be under positive pressure so it can directly be expanded through the fluidic device.

High or Low Pressure Steam

If a steam line is available either high or low pressure the steam can be used in a nozzle, venturi, or ejector to produce the vacuum which is needed for the operation of the fluidic gas sensor.

Water Lines

If water lines are handy they can be used by having the water flow through a nozzle, venturi or ejector to produce the vacuum needed to operate the fluidic sensors.

This had to be done when the fluidic gas sensors were used in the field to monitor hydrogen clouds in connection with the auto-ignition experiments carried out at the Kennedy Space Center. The only source available was a water line to which a garden hose could be connected to allow the mounting of the gas sensor where it was needed. A water ejector or aspirator was used to provide the vacuum needed for the operation of the oscillators.

In this last case the water pressure varied quite a bit so that a surge tank was added on the vacuum side. Thus the fluidic oscillator saw essentially a constant vacuum and operated at a constant pressure differential across it.

Ejectors

Fig. 43 shows a few commercially available water ejectors or

aspirators and they, when connected to an ordinary faucet or garden hose will provide the needed vacuum for operation of the fluidic oscillators. These ejectors can also be used on compressed air, gas or steam but are not very efficient since their gas consumption is rather high.

Fig. 44 A and B shows a few ejectors designed for gas supply and they will much more efficiently provide the vacuum to operate the fluidic oscillators.

Sandwich Modules

The commercial ejectors discussed above are units by themselves and must be connected by flexible hose to the fluidic gas sensor. They can be mounted right next to the sensor or some distance apart. The ejectors designed under this project are made about the same size as the gas sensor and can be mounted right together as an integral unit with internal connecting ports and the only connection to the device is a pressure line and leading away is the electrical wire carrying the signal from the transducer, Fig. 45. Somewhat more noise was observed when the latter design of the very compact sandwich was used. It is believed however that the noise can be reduced by internal isolation techniques.

EXPERIMENTAL APPARATUS AND EQUIPMENT

Introduction

To test and evaluate the fluidic oscillators and to determine their characteristics two laboratory set-ups were used. These laboratory systems had to be able to allow for accurate mixing ratios of gases so that the gas compositions were known down to parts per million and the signal from the transducer had to be analyzed with great enough accuracy

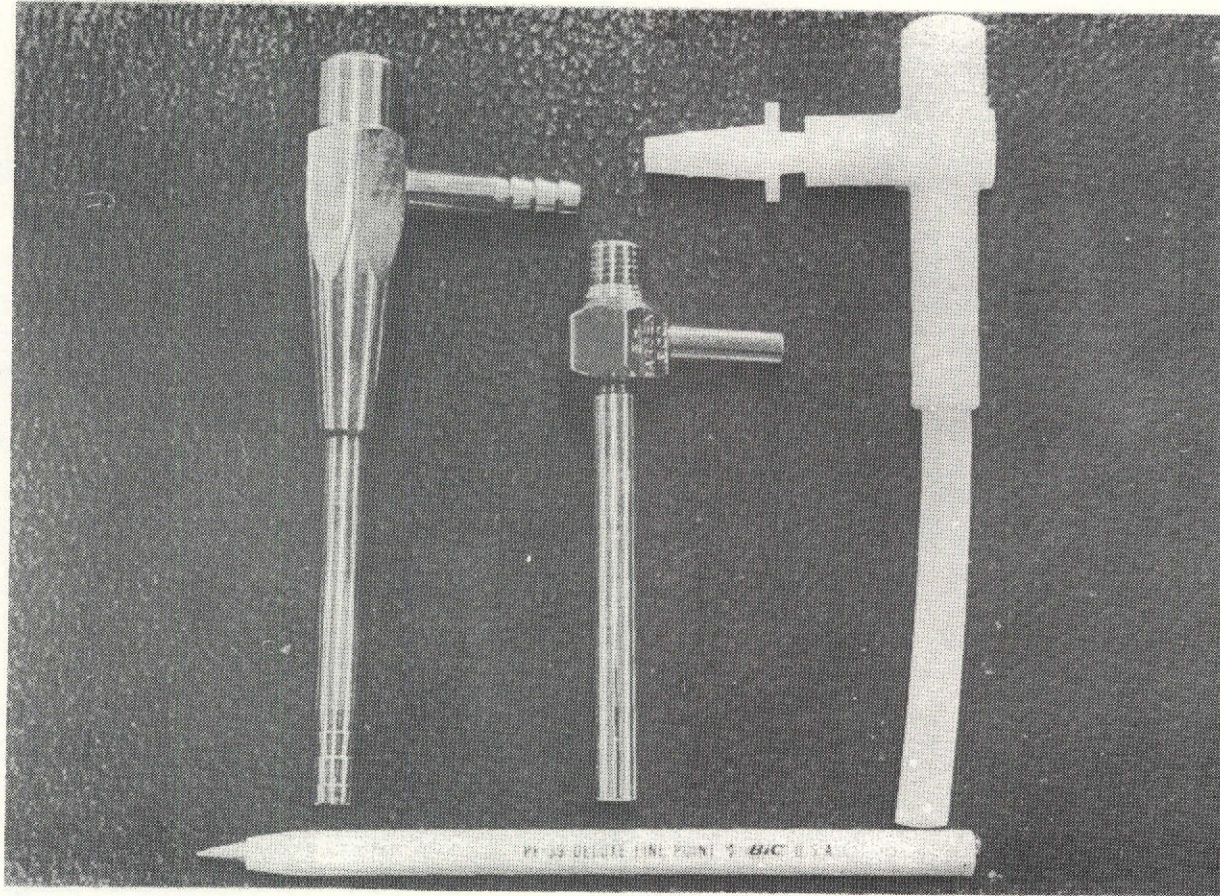
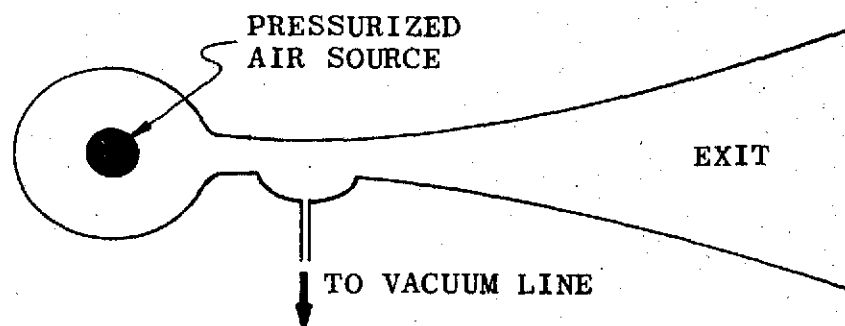
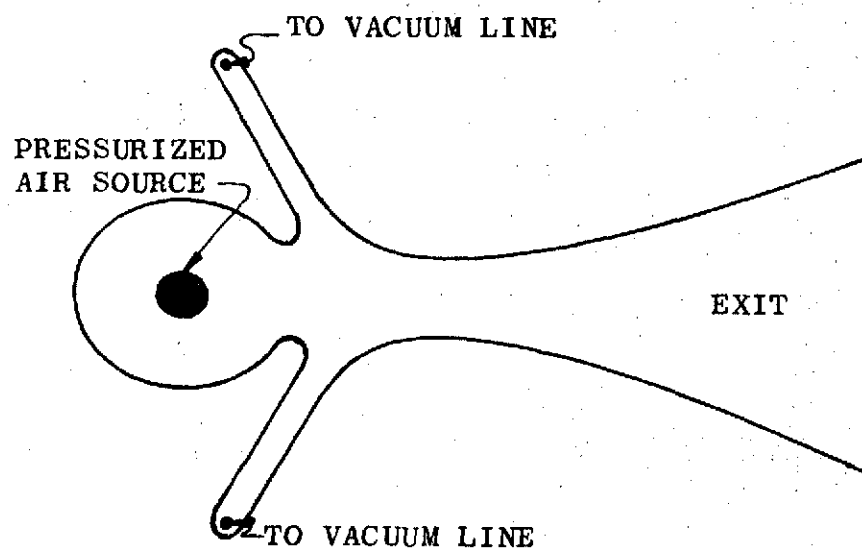


Fig. 43 Water Ejectors



CONVERGENT-DIVERGENT NOZZLE (ASPIRATOR)



EJECTOR

Fig. 44-A Ejector Design, Sketch

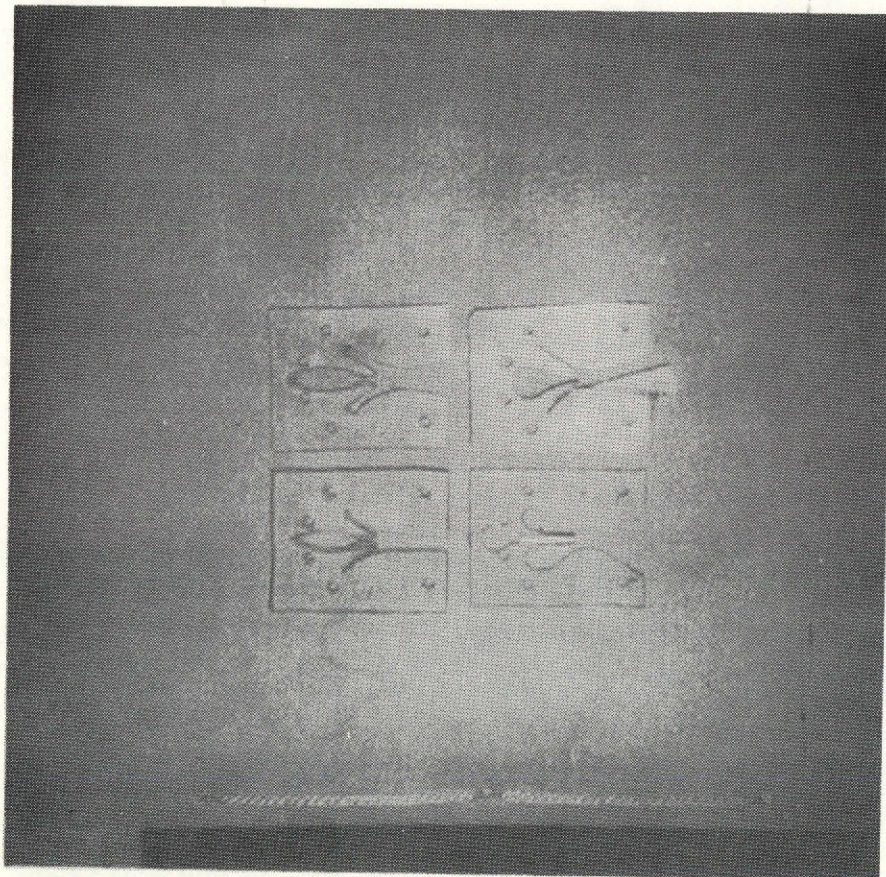


Fig. 44-B Ejector Design, Photograph

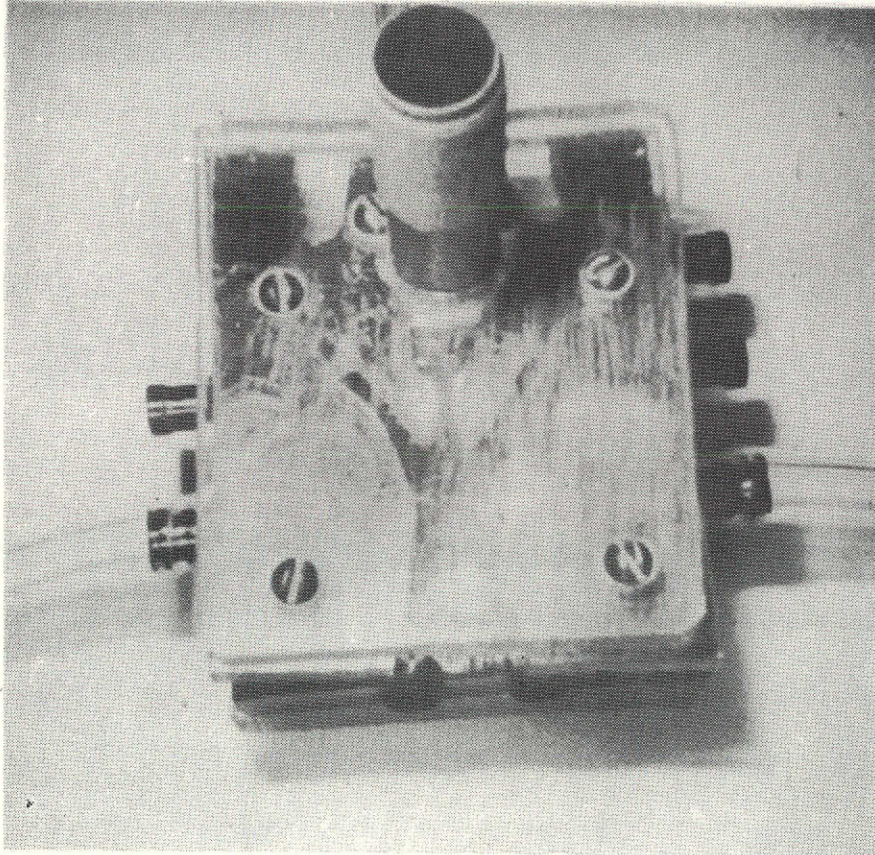


Fig. 45 Sandwich Design (Ejector & Oscillator Combined)

to detect the changes in frequency with gas concentration or other parameters of interest. To analyze the signal from the transducer an oscilloscope was used which displayed the signal trace and showed the purity of the sine wave or distortion, noise, etc. A Polaroid camera attached to this oscilloscope allowed the taking of pictures of the traces for detailed analysis and for the permanent record.

The signal from the transducer was also fed to a digital electronic counter which gave a direct read-out of the frequency at which the gas sensor was operating.

For most cases in this study with sensors operating at frequencies of somewhat more than 16,000 Hz the signal was strong enough so it could be used directly. However in the field when a 1000 ft transmission line had to be used a pre-amplifier was used to change the signal to a low impedance for transmission.

The Positive Displacement System

One of the methods used to determine the fluidic gas sensor characteristics was the positive displacement method. A glass jar was inverted in a water bath. This jar originally completely filled with water which was saturated with the gases to be used was then filled with each gas in turn. By this method the proportions of each gas could be determined very accurately on the volume scale on the side of the glass jar. The glass jar had a counterweight which allowed control of the pressure inside of the jar within certain limits. One could run the experiment at atmospheric pressure above and below.

A stirring motor, which was explosion proof since some of the mixtures used were of the explosive type, kept the gases in the jar well

mixed at all times so that the mixture concentration remained constant.

Fig. 19.

During the oscillator operation the frequency could be determined, the flow rate by timing the motion of the bell jar, the pressure differential across the fluidic device and the signature of the signal.

The carefully prepared gas mixtures could then be made to flow through the gas sensor either by forcing them through by pressurizing the gas by submerging the bell jar or could be made to flow through the fluidic device by applying a vacuum at the exit of the device.

This vacuum was produced by a vacuum pump in some cases and by ejectors in other cases.

Fig. 46 shows the system which allows the testing of the fluidic oscillator with positive pressure either by supplying pure gases or a mixture or by providing a vacuum by means of a vacuum pump or an ejector. The surge tank evens out any pulsations from the pump or the fluctuations of the supply pressure for the ejector. Positive pressure sources may easily be regulated by commercial regulators. A needle valve has been placed in the line to control the pressure across the oscillator so that the pressure versus frequency response can be obtained.

The Steady Flow System

The second system developed for the evaluation of the fluidic gas sensors is the steady flow system shown in Fig. 47 and Fig. 48. Each of the orifices in the system has been calibrated and the pressure across each is determined by a monometer. Once the pressure differential is known the flow rate is given since the supply pressure is held constant by regulators on the compressed gas tanks (N_2 , He, H_2 , etc.). Shut-off valves are inserted at different

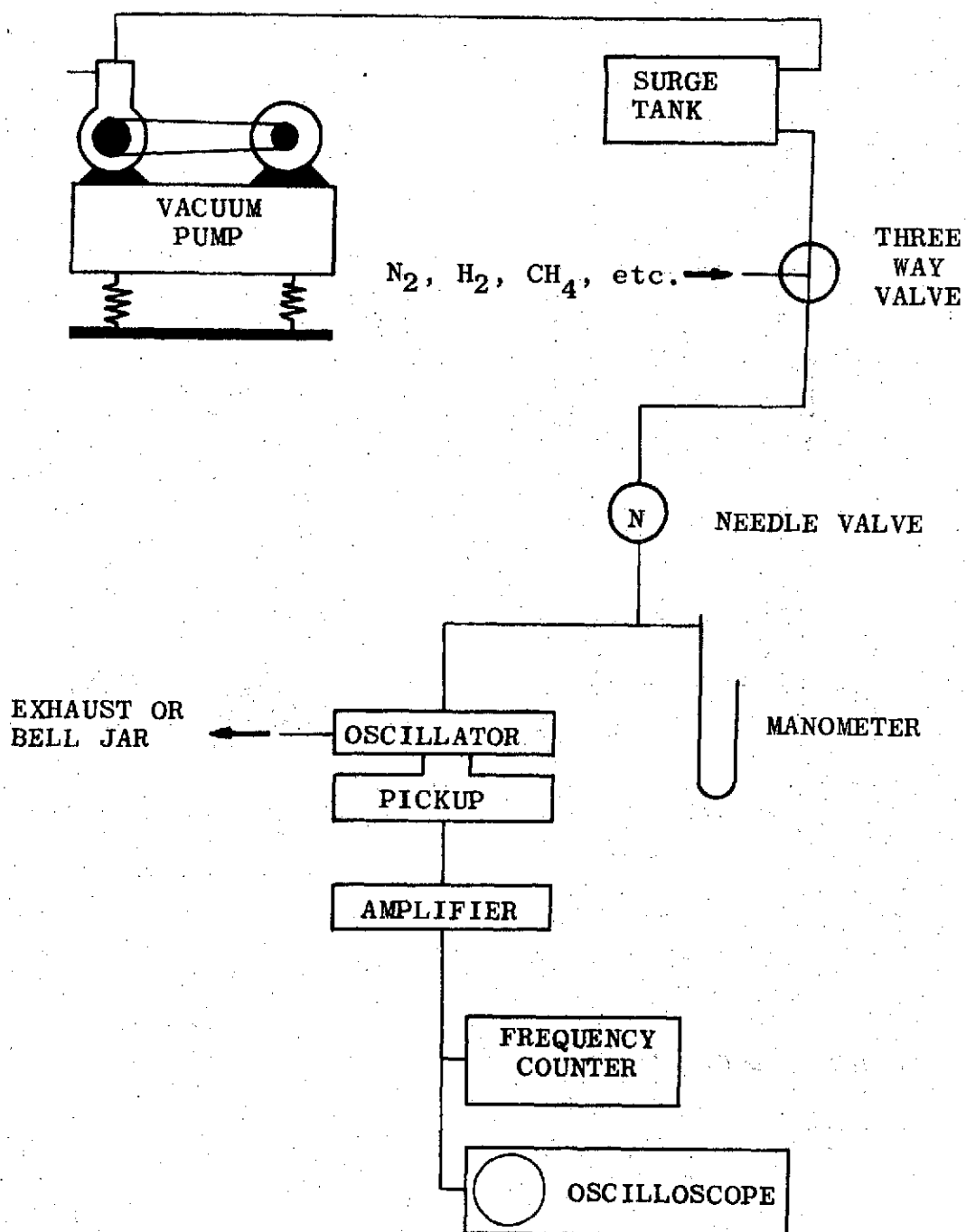


Fig. 46 Positive Displacement System

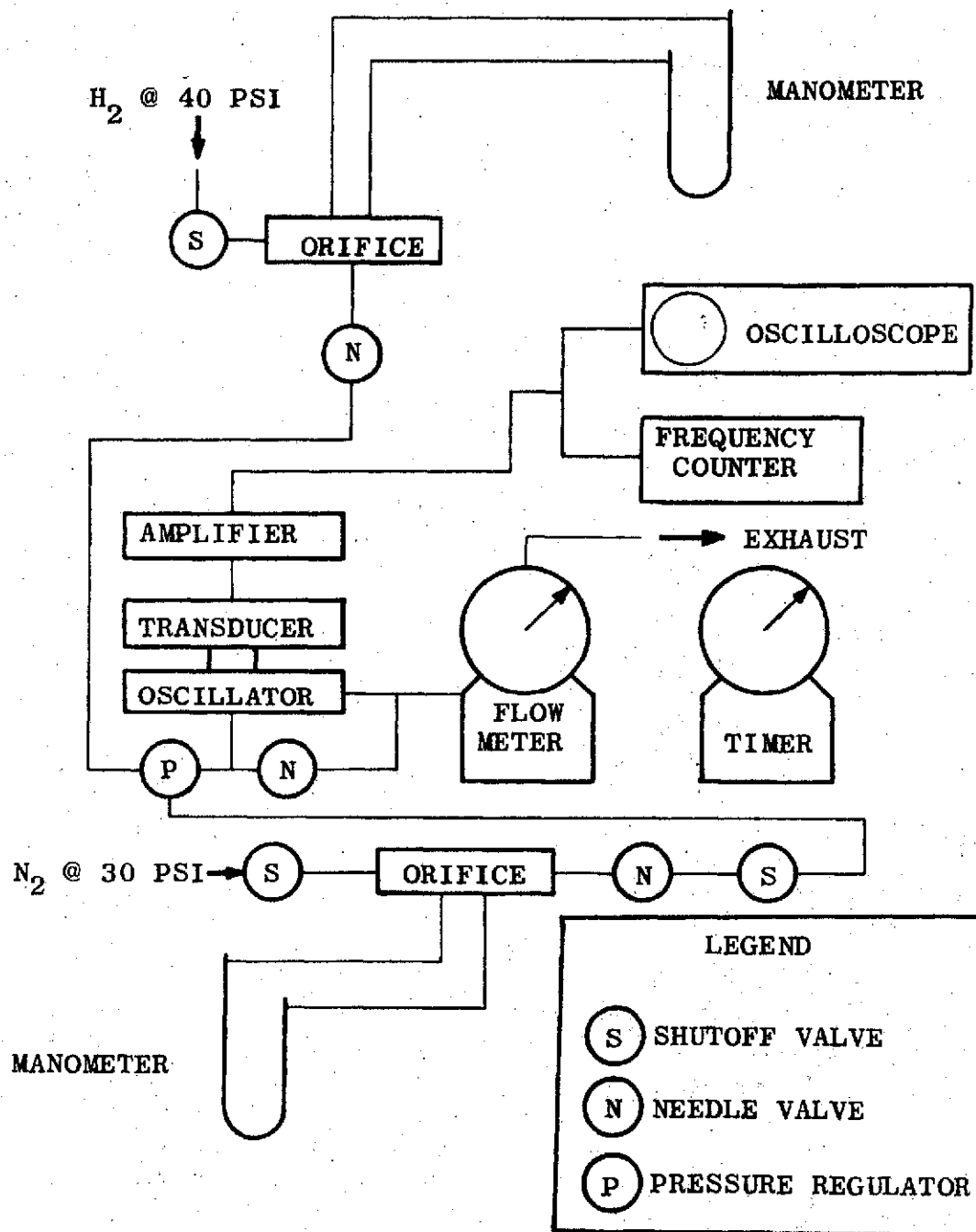


Fig. 47 Steady Flow System

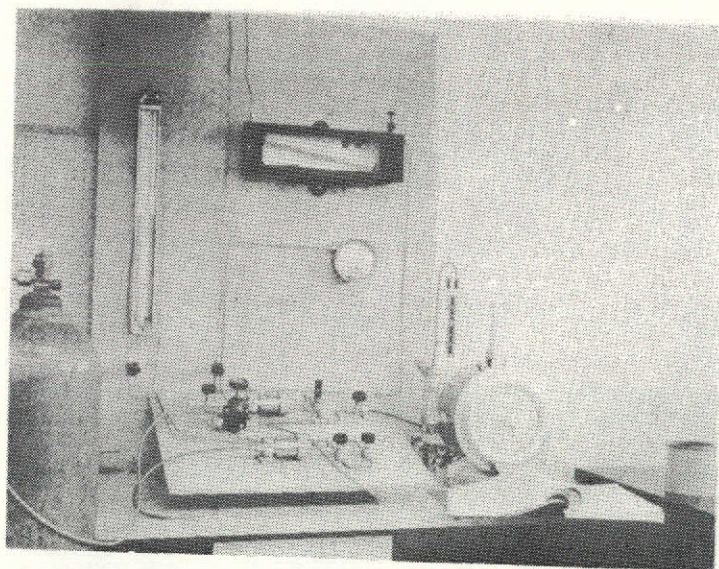


Fig. 48 Steady Flow System Photograph

points within the system so that pressure can be cut off without changing the needle valve settings. The operation of the system is initiated by making certain that the shut-off valves in the system are all closed. The regulators on the hydrogen and nitrogen bottles are set to 30 and 40 psig respectively. If the needle valves have not been previously set, they should be closed. The pressure regulator in the system should also be shut down to prevent flow in the system. The shut-off valves should all be opened to their fullest extent. Care must be exercised or the manometers will overflow due to the excessive pressures occurring on one side of the orifice. The needle valve on the nitrogen side of the system should be partially opened, and the regulator partially opened so that flow will take place. Adjustment between the settings of the pressure regulator and needle valve will be required to obtain the correct amount of flow. That flow which is obtained when the oscillator is operating with a signal of satisfactory amplitude is the desired flow of nitrogen. The by-pass valve around the oscillator may be used to obtain the proper signal amplitude. Since the by-pass valve does not effect the mixture ratios it can be conveniently varied at will. It should be noted that all flow passes through the flow meter in order to double check the results obtained. The flow of hydrogen may now be initiated into the system by opening the needle valve on the hydrogen side.

Manometer, flow, and frequency data are obtained to determine the response characteristics of the oscillator to hydrogen. A similar procedure can be used to determine the response characteristics of the oscillator to helium. The results of response curves were previously shown.

DETECTION OF GH_2 in TERTIARY MIXTURESDetection of GH_2 and GHe in the Presence of Other Gases

It is necessary to determine the presence of hydrogen not only in the presence of nitrogen, which is often used as a purge gas, but also in the presence of trace amounts of other gases such as helium. Helium, because of its lightness and other physical properties will sometimes cause hydrogen detectors to act as if hydrogen is present, thus causing alarms to be activated unnecessarily.

In order to use a fluidic oscillator to detect the presence of one gas mixed with another, if both gases are known, it is only necessary to determine the change in frequency of the oscillator. This is sufficient to determine the percentage change in the composition of the mixture. If, however, it is required to also detect the presence of a third gas, it is no longer sufficient to simply record the change in frequency because the change could occur from many different combinations of the helium or hydrogen. Therefore in order to determine the composition of the known mixture, it is necessary to conduct another independent experiment. In order to determine what type of experiment should be performed, it was decided to make an extensive search of the literature. The results of that experiment combined with the frequency change obtained from the fluidic oscillator would yield sufficient information to determine the exact composition of the mixture.

After a lengthy literature search the following list of methods were selected as possible candidates for the second experiment. They are listed below in four broad categories.

- A. a. Pd wire, resistance changes with H_2 concentration
- b. Pd-Ag bimetallic strip

- B. a. Variation in heat conductivity
- C. a. Reduction of CuO by H₂
 - b. Reduction of other metallic oxides such as CoO
 - c. Use of depleted uranium
- D. a. Use of porcelain bacteriological thimble, with maximum pore dimension of 1.3 microns
 - b. Use of spectral analysis
 - c. Use of absorption microcell for the detection of H₂ (Fuel Cell)
 - d. Liquification of gaseous components
 - e. Use of a permeable membrane
 - f. Diffusion separators

The above summary constituted the most promising processes discussed in the literature. Others were cited, however their application was so limited that it would prove of little use in the present application.

In category A, the properties of palladium and its alloys are used to detect the presence of hydrogen. Palladium wire can be used to detect hydrogen even in the presence of helium. The device operates on the principle that when hydrogen is absorbed on the wire, the resistance changes. The change can be measured so as to determine if hydrogen is present.

Palladium when combined with Ag and made up into a bimetallic strip, can also be used to detect the presence of hydrogen. The article does not indicate the effect of helium. It, however, does state that the bimetallic strip has been used to detect hydrogen in concentrations as low as 50 ppm.

In category B, the variation of thermal conductivity is used to determine the concentration of hydrogen in a mixture. Because of the large difference in the thermal conductivities of nitrogen and hydrogen measurements of thermal conductivity to determine hydrogen concentrations can be accurate to 10 ppm. However, since the thermal conductivity of hydrogen is only 10% greater than that of helium this procedure would not be expected to obtain the same accuracy between these gases.

In category C are lumped those processes which through oxidation or reduction will remove hydrogen from the system. Hydrogen removal can occur through either the reduction of CuO or other metallic oxides such as CoO or through the oxidation of uranium by hydrogen. The former process is relatively well known from elementary chemistry. The reduction of CuO by hydrogen is a process that has an end result of Cu and water.

The process occurs at room temperature, however, because of the absorption of the resulting water vapor, the surface is coated with water which rapidly prevents further reaction. Thus it is necessary to raise the temperature near 212°F in order to drive the absorbed water out and permit the reaction to continue. This process will continue to remove hydrogen as long as CuO is present. Eventual replenishment is necessary and under certain conditions this may be inconvenient. The latter method described above uses depleted sintered uranium is of special interest since when once placed in the system it can be indefinitely revitalized from a remote position. This of course is a distinct advantage over the similar system utilizing CuO . The system works as follows if it is desired to determine if there is He in the system, the sintered uranium is heated to between 200° and 250°C . Under this condition

UH_3 is formed, thus removing hydrogen from the system. When the test is completed, hydrogen may be driven out of uranium by heating to between 300° and 400°C . The hydrogen released from the uranium permits the system to be used over many times.

In category D are other methodologies such as diffusion separators, porcelain bacteriological thimbles, fuel cells, permeable membranes, etc. These methods are considered of doubtful value, because of their bulk, slowness or insufficient development data which appears to make them, at this time, poor choices for any significant commitment. They may, at some future time, prove useful.

The CuO reduction system was chosen as the most feasible procedure for the demonstration that fluidic oscillators can be used to detect hydrogen in the presence of helium and nitrogen. Since the CuO is also readily available and poses no other problems it was selected for use in the demonstration for this study.

The procedure, test apparatus and calculations made to determine the amount of nitrogen, hydrogen, and helium in a gas mixture with CuO is described carefully below.

Fluidic Concentration Determination of the Components in a Mixture of N_2 , H_2 , and He through CuO Reduction

In some cases there may be H_2 in He or both of these gases in a nitrogen or air atmosphere. Under those conditions it will be necessary to be able to establish the concentration of the H_2 in the mixture of gases. This is so because the H_2 may produce a hazardous condition while the He does not. Presently used sensors have many drawbacks for the separation of He and H_2 . They either become confused

by the presence of both gases and cannot distinguish between them or are so slow that a fire and or explosion may have occurred before the presence of the hydrogen has been detected.

For the separate detection of the concentration of He and the concentration of H_2 two fluidic oscillators were used. The first one senses the mixture as it is. Then the gas mixture is passed through a filter which will absorb some portion of the H_2 and then through the second fluidic oscillator.

Since both oscillators are calibrated for frequency changes with He and with H_2 concentrations their respective deviation from the base frequency allows the determination of both the amounts of He and H_2 present.

For the purpose of demonstrating this method a system using CuO which is used to oxidize part of the H_2 in the system proved to be very satisfactory performing as expected.

Fig. 49 presents a schematic sketch of the system indicating the flow paths of the gas mixture and the location of the fluidic oscillators. Fig. 50 shows the separation column a photograph to indicate what the system actually looks like.

In the actual operation the CuO is first heated (for convenience by an electric coil which can be completely sealed) to about 220°F. Although the reaction between the CuO and H_2 occurs near room temperature, the reaction product is water and this water will adhere to the CuO matrix unless it is driven off by heat. A cooling bath is provided so that the initial gas mixture and the treated one (the one which had some of the H_2 removed) are at the same temperature. This procedure simplifies the data interpretation since no temperature corrections are necessary.

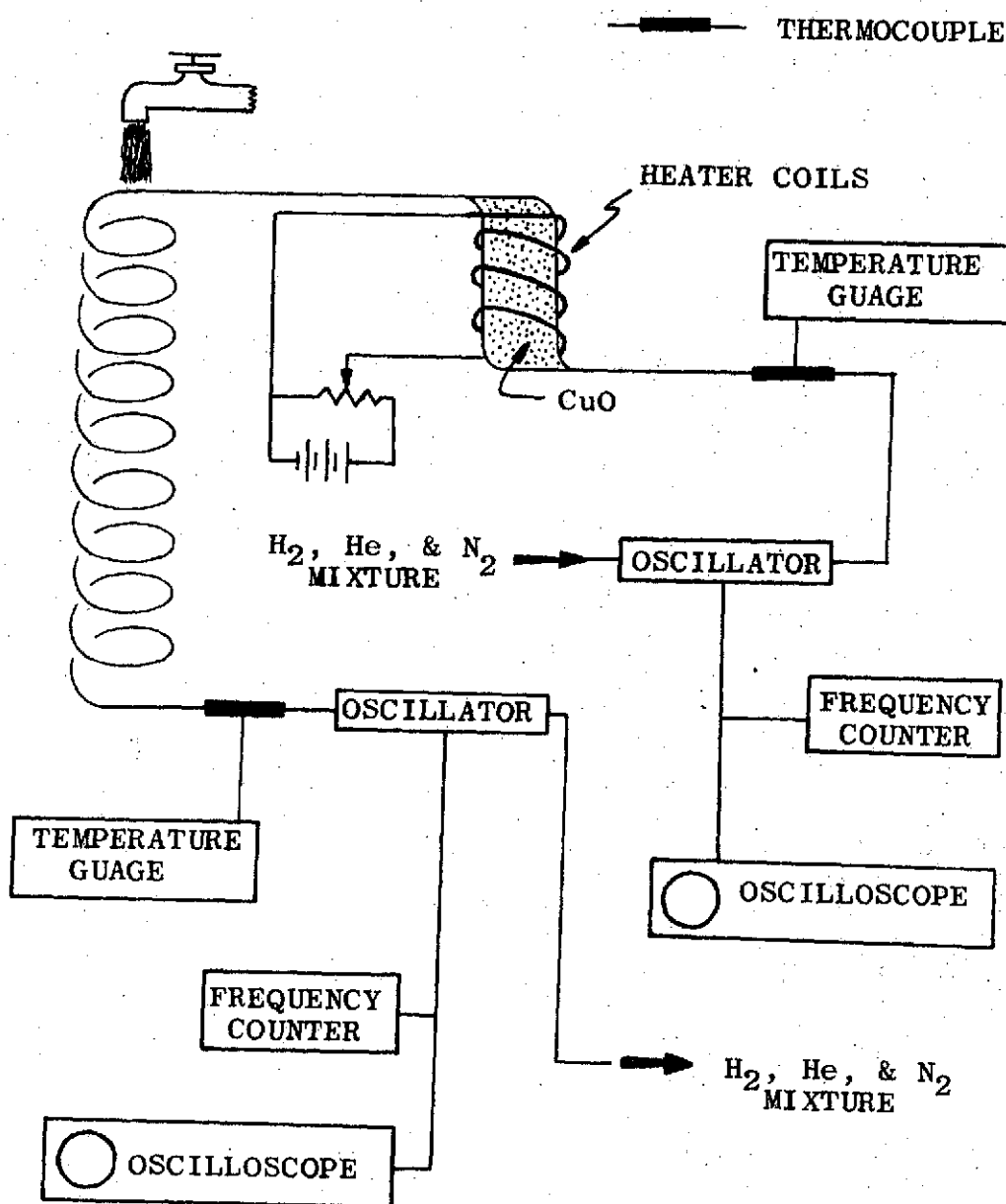


Fig. 49 H_2 -He Separation and Concentration Metering System

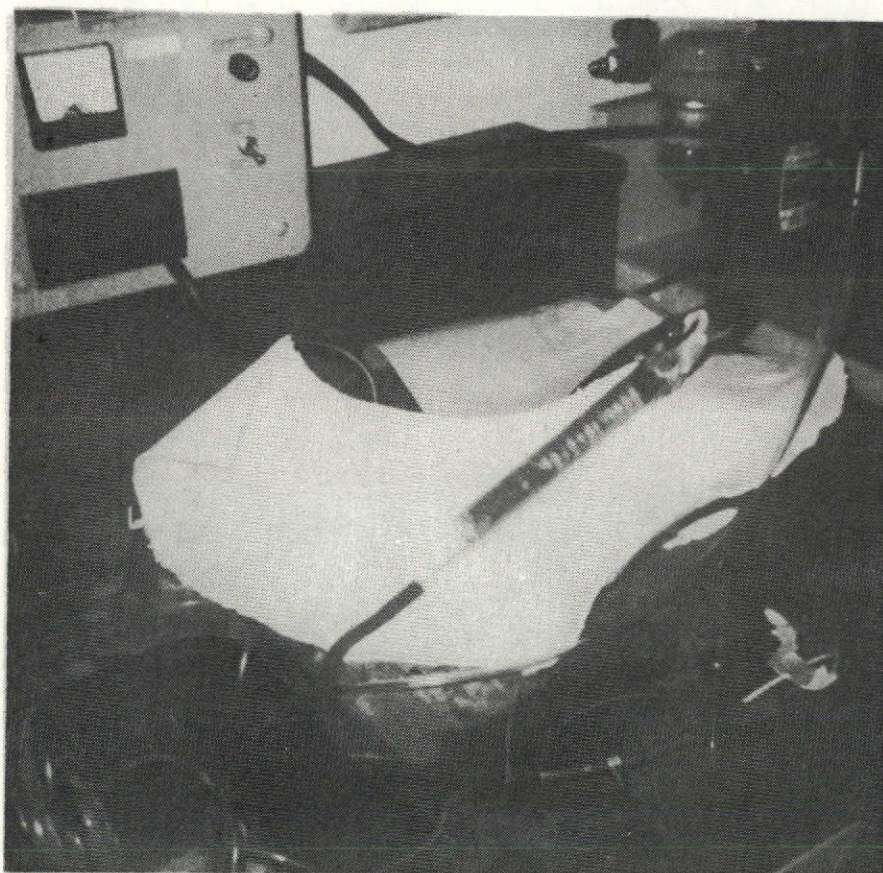


Fig. 50 Separation Column, Photograph

In the test set-up nitrogen flow is initiated at a rate so that both oscillators A and B will oscillate. Helium flow is then initiated. Since the Helium does not interact with the CuO the amount of Helium can be determined by using the previous calibration of the oscillators. If then Hydrogen is permitted to flow through the calibrated orifice the amount of H_2 flowing through the system is independently known. The system is designed so that each gas source can be controlled independently without effecting the flow of the other gases.

As soon as the system stabilizes the total change in the oscillator frequencies can be measured.

Fig. 51 schematically indicates these phenomena and the mathematical formulation of them.

Δf measured from base $f(H_2)$

$$\Delta f_1 = \left(\frac{\partial f}{\partial H_{e_1}} \right) \Delta H_{e_1} + \left(\frac{\partial f}{\partial H_{2c_1}} \right) \Delta H_{2c_1} \quad (39)$$

$$\Delta f_2 = \left(\frac{\partial f}{\partial H_{e_2}} \right) \Delta H_{e_2} + \left(\frac{\partial f}{\partial H_{2c_2}} \right) \Delta H_{2c_2} \quad (40)$$

$$\begin{cases} \Delta H_{2c_2} \cong \Delta H_{2c_1} - \Delta H_{ABS} \\ \Delta H_{e_2} \cong \Delta H_{e_1} \end{cases} \quad (41)$$

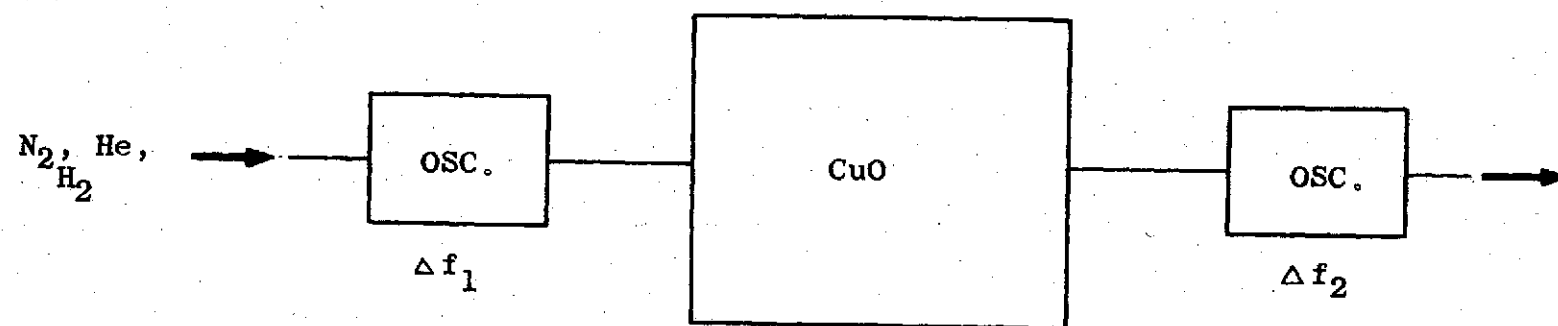


Fig. 51 H_2 -He Separation System

Since only small concentrations of hydrogen and helium are to be detected the equations (39) and (40) can be linearized and the subscripts (1) and (2) refer to oscillators (A) and (B) respectively. For the linearized equations $\frac{\partial f}{\partial He_c}$ and $\frac{\partial f}{\partial H_2_c}$ have been determined by previous tests and their values may be given respectively as 0.03125 and 0.04.

Tests conducted with the experimental apparatus as shown in Fig. 49 resulted in a reduction of approximately 9.4% of the hydrogen when flowing over the CuO for the flowrates and system used. The actual variation obtained for different concentrations of hydrogen are shown in Fig. 52.

The equations for the two oscillators (A) before the CuO absorption chamber and (B) after the absorption chamber become

$$\Delta f_A = 0.03125 \Delta He_c + 0.04 \Delta H_2_c \quad (42)$$

$$\Delta f_B = 0.03125 \Delta He_c + 0.04 \Delta H_2_c + 0.906 \quad (43)$$

Since the cooling coils brought the temperature of the gas mixture back to its original temperature when it entered (B), no temperature effect need to be included. If this is not done other terms must be added to the equation for oscillator (B). The term added will be a constant for a given experimental arrangement.

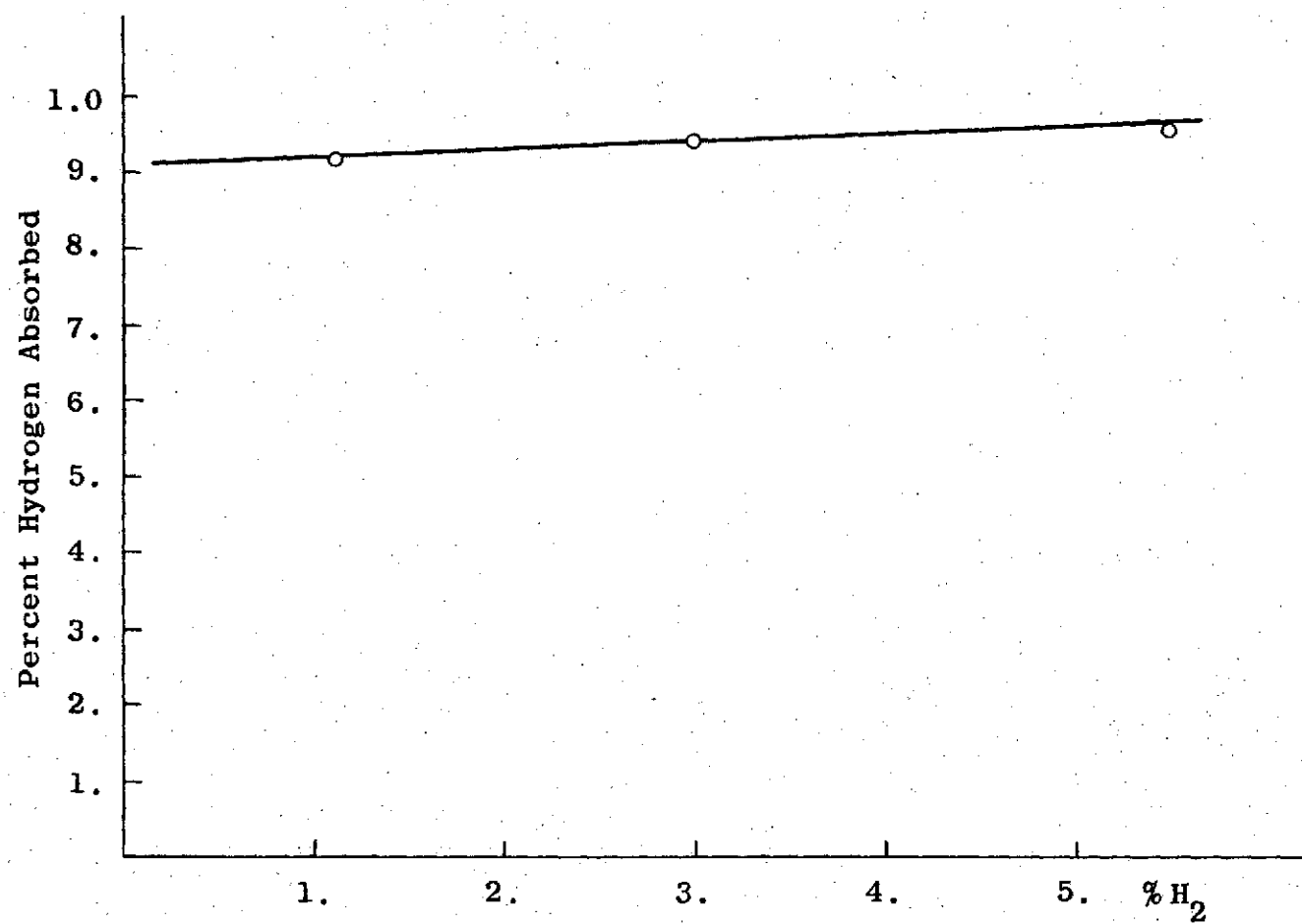


Fig. 52 Hydrogen Absorbed in the Separation Column

When the equations (42) and (43) are subtracted the resulting equation may be written as

$$(\Delta f_A - \Delta f_B) = 0.04 \Delta H_{2c} (0.094) \quad (44)$$

Thus from the above equation the hydrogen concentration ΔH_{2c} may be determined.

$$\Delta H_{2c} = 265.96 (\Delta f_A - \Delta f_B) \quad (45)$$

Fig. 53 gives the results of two oscillators used in this system but operating at slightly different frequency. It can be seen with only N_2 the oscillators operate at their base frequencies. Then with He added the frequencies increase and do so proportionately since each oscillator sees the same mixture. When, however, H_2 is added the CuO filter absorbs some of the H_2 before it gets to the second oscillator and so it sees a different mixture composition. Graphically this can be observed by the considerable change in slope of the lines connecting the frequency points for different mixture compositions.

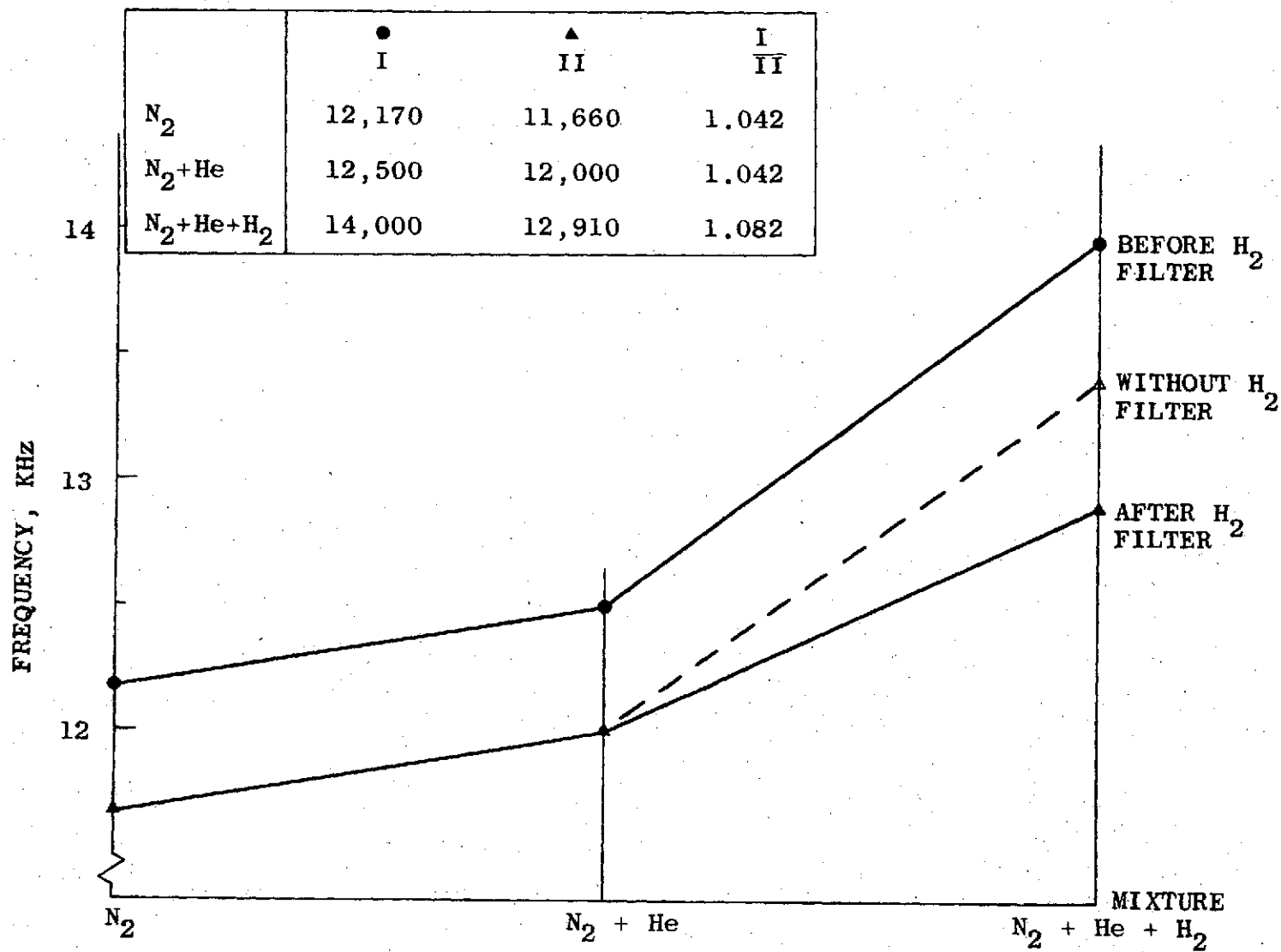


Fig. 53 H_2 -He Separation and Concentration Determination

EFFECT OF THE ENVIRONMENT

Environmental conditions or changes in the environment can have an effect upon the fluidic oscillator. If desirable it could even be made to be a sensor for such changes, at other times, however, it is desirable to have the oscillator not effected by these environmental changes and only have it sensitive to the particular parameter under study. Much can be done through design, isolation and operating range and conditions to bring out these factors or suppress them. Some of them are mentioned below.

Pressure

The operating pressure of a fluidic oscillator may effect the frequency at which it oscillates and changes in this pressure may change the oscillator frequency. Thus the oscillator can be a pressure sensor. On the other hand if pressure changes are not to effect the oscillating frequency several methods can be used to provide this.

If a constant pressure source, well regulated is available then this problem does not exist. If the pressure source changes a surge tank can be interposed between the source and the fluidic device and the pressure changes will be damped out by the time it gets to the fluidic oscillator. Another possibility is to operate the oscillator, and this is especially convenient when using the fluidic device as a sniffer, with the exit pressure below the critical pressure of the primary nozzle. In this manner any pressure variations on the downstream side will not effect the flow rates and thus give a stable frequency. Putting resistances, capacitances and inductances in the feedback loop and adjusting these values it is possible to eliminate these effects and make the fluidic device pressure insensitive. See the frequency vs

pressure plots.

Temperature

Basically the fluidic oscillators are able to sense changes in temperature since the wave propagation velocity is related to the speed of sound. This variation is proportional to the square root of the absolute temperature. This effect can be enhanced or suppressed as above through proper design and operating range and conditions. The oscillator can be made a temperature sensor or to be very insensitive to temperature.

Since the temperature effect can be predicted by theory it can be cancelled out also by the electronic conditioning of the signal as long as there is a temperature sensor (thermocouple) near the sensor. Another alternative is the use of two fluidic oscillators with the same temperature effect and they can be beating against each other so that their change in frequency due to temperature does not have any effect upon the beat frequency.

Fig. 54 shows the test set-up and Fig. 55 the uncorrected or unsuppressed temperature frequency variation for the M type oscillator and how the theoretical prediction and the experimental data agree.

Humidity

Humidity has a relatively small effect upon the frequency in the normal range of variation. It has its effect through the effected density change which is always rather small. Fig. 56 gives a graph which shows the effect of humidity upon the sonic velocity which plays an important role in the performance characteristics of the fluidic oscillator. This is plotted against H_2 content and indicates that a change of 100% in Relative Humidity which is impossible to encounter has only about one half of one percent effect upon the velocity of sound.

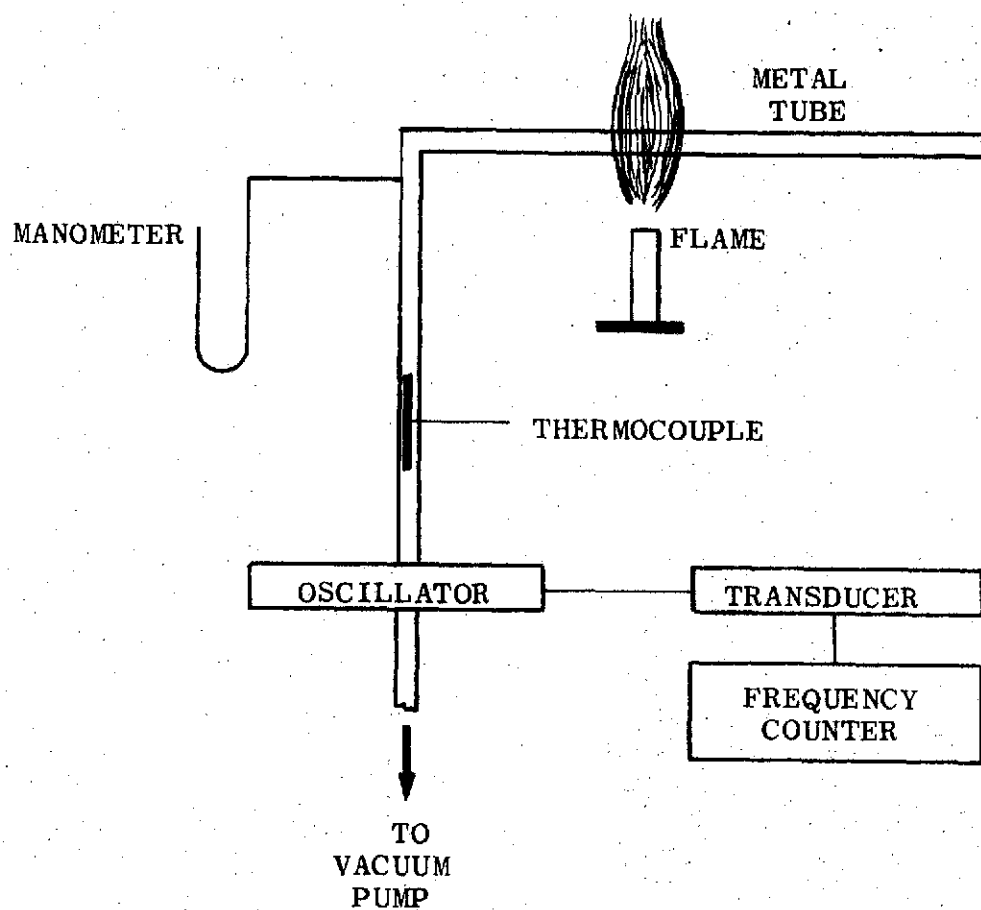


Fig. 54 Temperature Effect Test Set-up

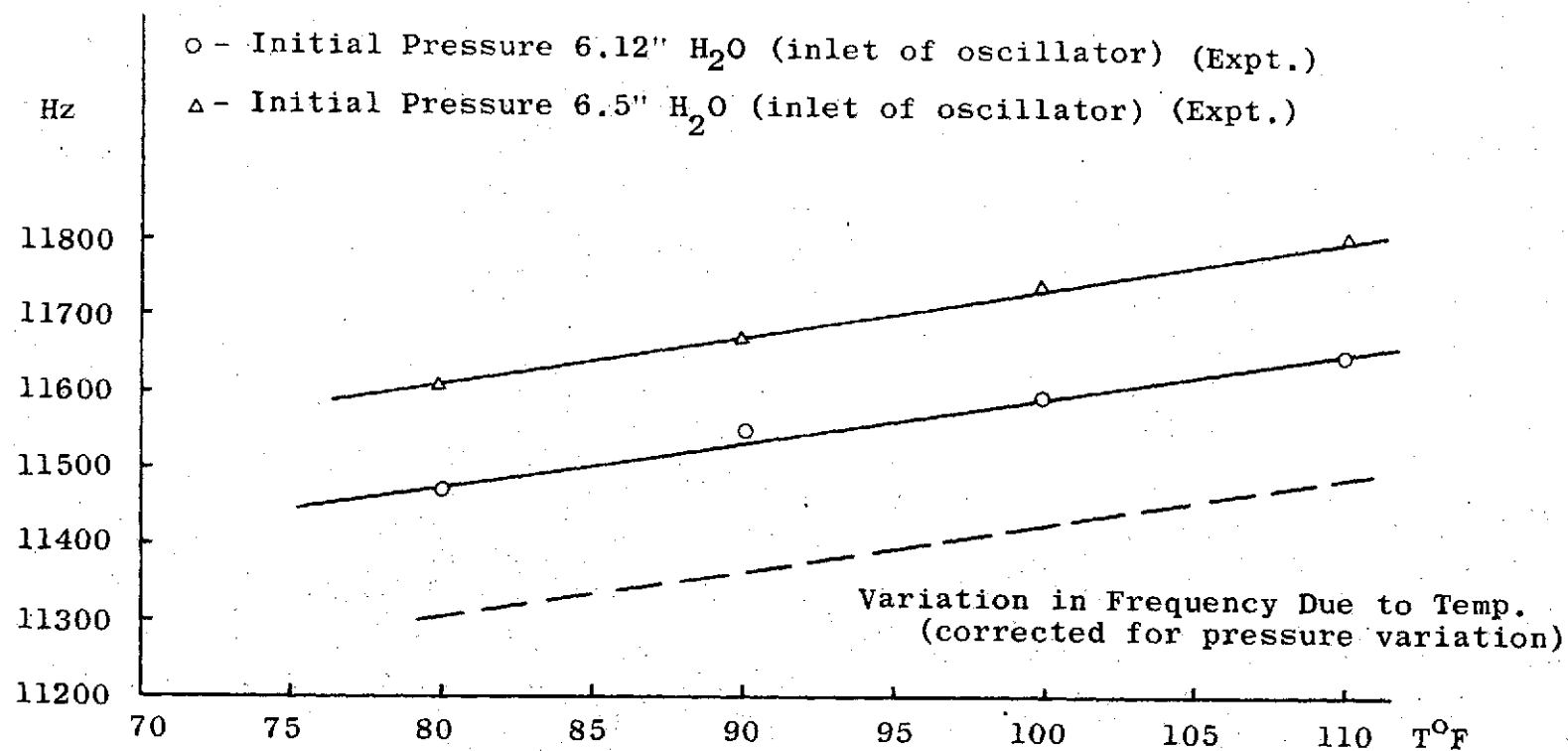


Fig. 55 Frequency versus Temperature Variation

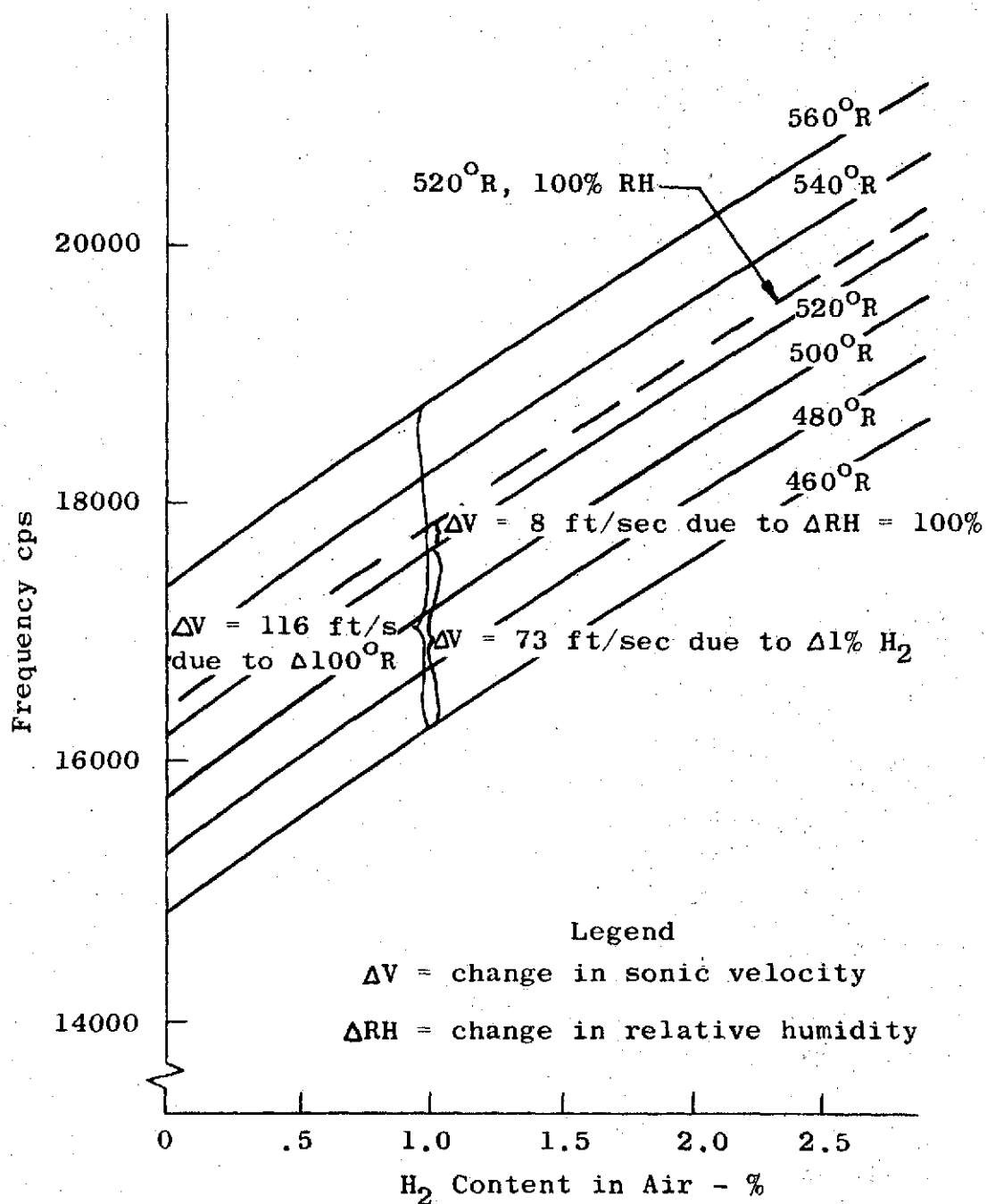


Fig. 56 Humidity Effect upon the Frequency

Wind

It is foreseen that these oscillators, if widely used, will be placed in situations where they will be exposed to wind.

In order to develop meaningful data a fan was used and the oscillator oriented from 0 degrees (straight into the wind) to 180 degrees (straight downwind) and the frequency variation from base frequency recorded. Fig. 57. The variation in frequency was less than one half percent for 60 MPH wind velocity.

When a small vertical tube was placed over the inlet to the fluidic oscillator shielding from the wind by having the tube openings horizontal, no effect was noticed. Thus it seems feasible to shield the oscillator against wind.

If the unit is not shielded against wind some of the slow variations due to wind can be electronically filtered out of the signal from the transducer. The actual wind velocities were measured with a velometer. All tests indicated relative insensitivity to wind both velocity and direction.

Rain

Some of the oscillators were used in the rain during the auto-ignition experiments to sniff the H_2 cloud. It was noticed that on occasions the fluidic oscillator picket up a rain drop and momentarily the oscillation stopped or was greatly reduced for a small fraction of a second and then recovered by pulling the water through and operated as if it had never been disturbed. Thus it is a self healing device which even if momentarily disturbed will return to proper operating conditions in a short time. The sharp drops and rises were very typical and not easily confused with gas concentration measurements.

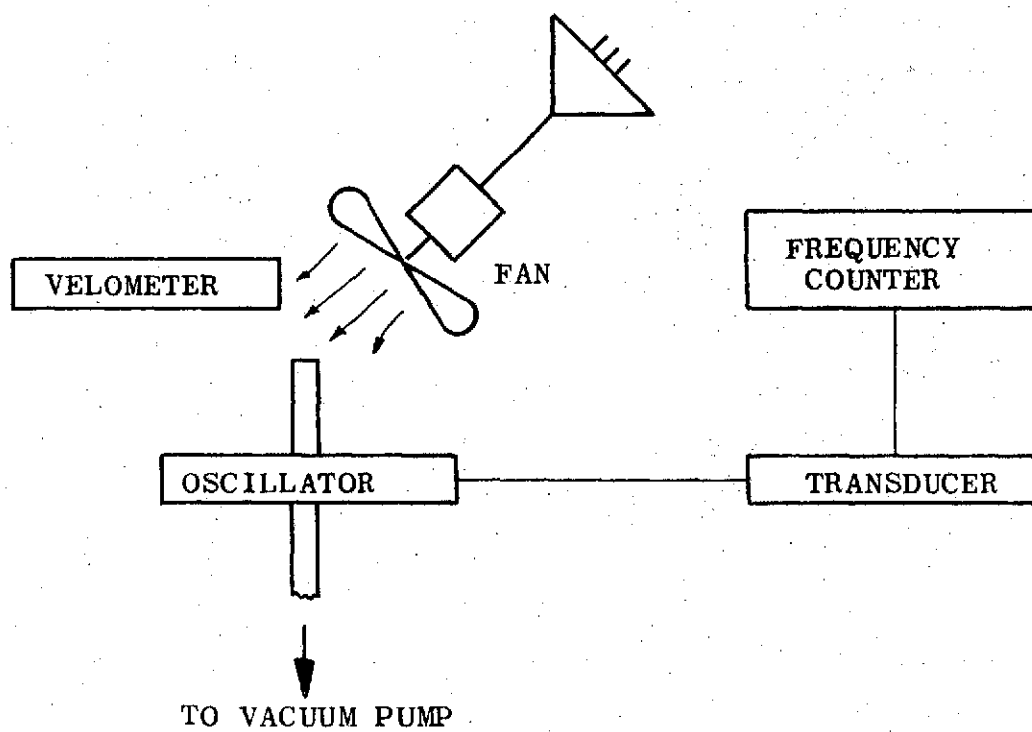


Fig. 57 Wind Effect Test Set-up

Dust

In the field tests which were carried out at the Kennedy Space Center under rather severe conditions dust never caused any difficulties. If a dust particle should be drawn in it would go right through the device at worst only momentarily disturbing the operation. If conditions should be extreme as in a sandblast area then filters could be put over or in front of the device or it could be designed with passages large enough to let the particles pass. Under those conditions slow and long range changes in the fluidic oscillator characteristics could occur by slow corrosion of the passage way walls.

Other environmental effects could possibly be thought of but the major ones were mentioned here and difficulties are not anticipated.

ELECTRONIC INSTRUMENTATION AND SIGNAL PROCESSING

Introduction

With the fluidic oscillator developed and operating properly with the required characteristics the results of the oscillator must be sent back to the central monitoring and control station. For this purpose it was necessary and most convenient to transduce the pressure pulses into an electrical signal. This signal was then sent, either directly or amplified, through a transmission line and finally processed to give read-out or operate some indicators or be recorded for later analysis.

To go to an electrical output is not necessary and not the only way but it was found most convenient in this investigation.

Transducer and Signal Amplification

The use of transducers to change the pressure pulses either direct or rectified from the fluidic oscillator - gas sensor into electrical output did not turn out to be a problem. The detectors or transducers used were earphones packaged by Callectro G.C. Electronics, a Division of Hydrometals Inc. and are normally used with transistor radios. These earphones are standard catalog items and are available at Lafayette Electronic Retail Stores for less than one dollar.

The signals generated by the F-1, F-2, and S-4 oscillators have sufficient amplitude that the transducers can be used without amplification as input to oscilloscopes, counters or tape recorders even after being transmitted through long transmission lines. The output under these conditions is from 0.22 to 1.5 volts.

For the M series or the high frequency feedback oscillators such as the S-6 signal amplification is required. The amplifier can be a commercial model or as shown here is a 70 DB amplifier designed and constructed in our laboratory. Fig. 58. An amplifier of this kind will be inexpensive. The actual amplitude of the output is controlled by a potentiometer to keep them from overloading the monitoring devices.

Signal Conditioning

After the signal is changed from pressure pulses to electrical signals, amplified or not as needed, the rest of the electronic instrumentation is more or less standard as needed for signal conditioning and processing to give the results in the desired form. A threshold signal can be used subsequently to trigger an alarm system based upon a predetermined hydrogen mixture level, or a continuous monitoring system may be employed to measure actual percentages of hydrogen in the mixture.

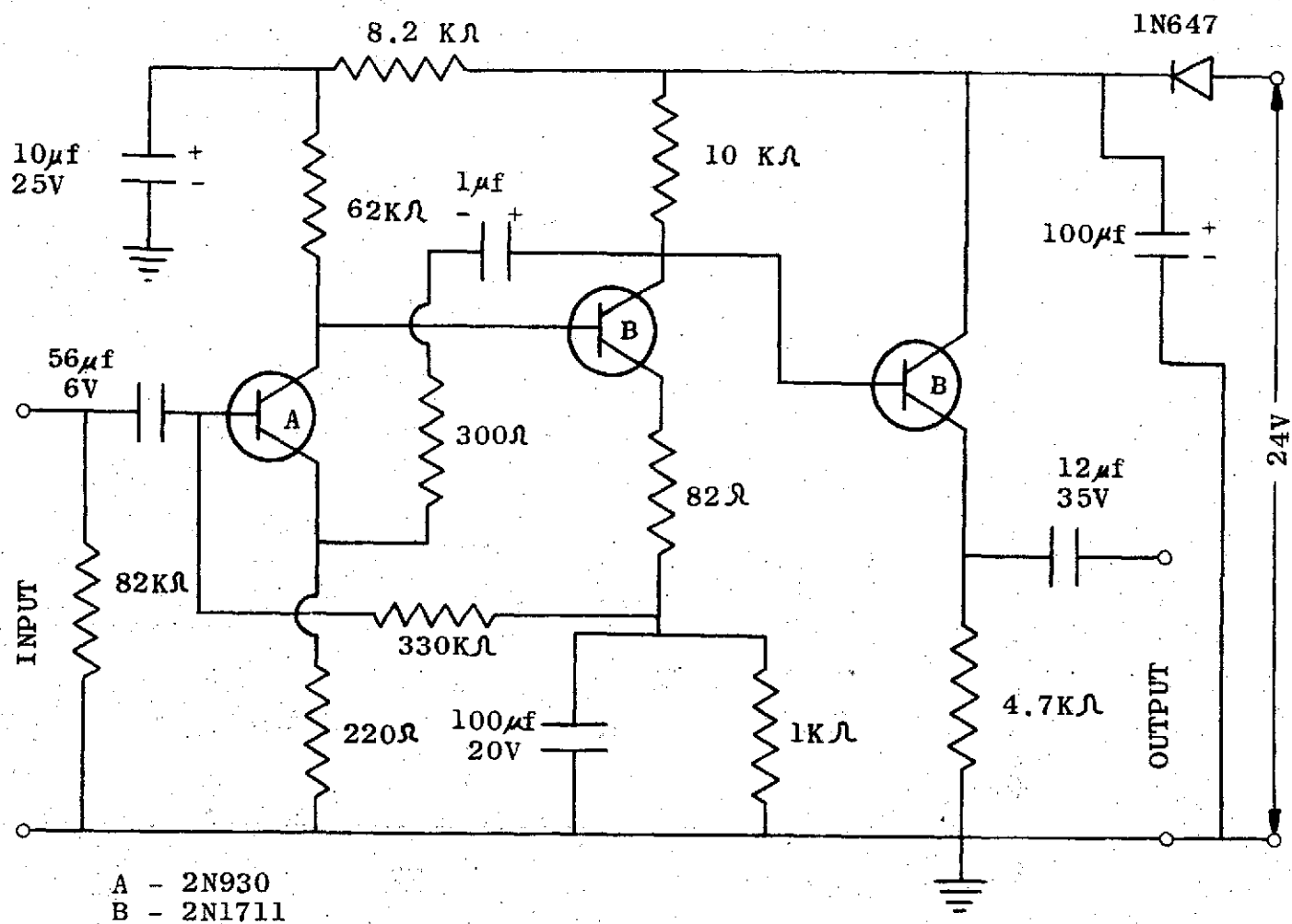


Fig. 58 Amplifier Circuit

The necessary control signals can be derived either from a tuned parallel LC resonant circuit or through a frequency discriminator.

Warning or Continuous Readout Systems

Fluidic Threshold Detector. The fluidic oscillation of the hydrogen detector is coupled acoustically to a magnetic or crystal pick-up delivering an electrical carrier signal of, let us say for the sensitivity desired here, 16,000 Hz for the base frequency in air. As hydrogen is introduced into the air, the carrier frequency increases as a function of the concentration in the mixture.

This frequency deviation can now be used in a threshold circuit to trigger an alarm for a preset hydrogen level. Fig. 59 shows a schematic diagram for such a fluidic threshold detector. The acoustical signal is coupled out from the fluidic detector and fed into the magnetic pick-up. This amplified or not amplified electrical signal of a frequency of about 16,000 Hz is passed through a LC tank circuit which is tuned to resonance at 16,000 Hz. Since this tuned LC circuit is in series with the signal path it will have maximum impedance at this frequency and act as a wave trap, blocking the signal. When, however, the gas concentration changes as hydrogen is introduced, the frequency will change and the tank circuit will now have an output which is subsequently rectified and then put across a threshold bias circuit which is adjustable.

If the frequency changes sufficiently because of the hydrogen concentration, the rectified output eventually exceeds the threshold level of the bias circuit and an output will become available to trigger the alarm circuit which could be in the form of a meter, a light or an audible sound.

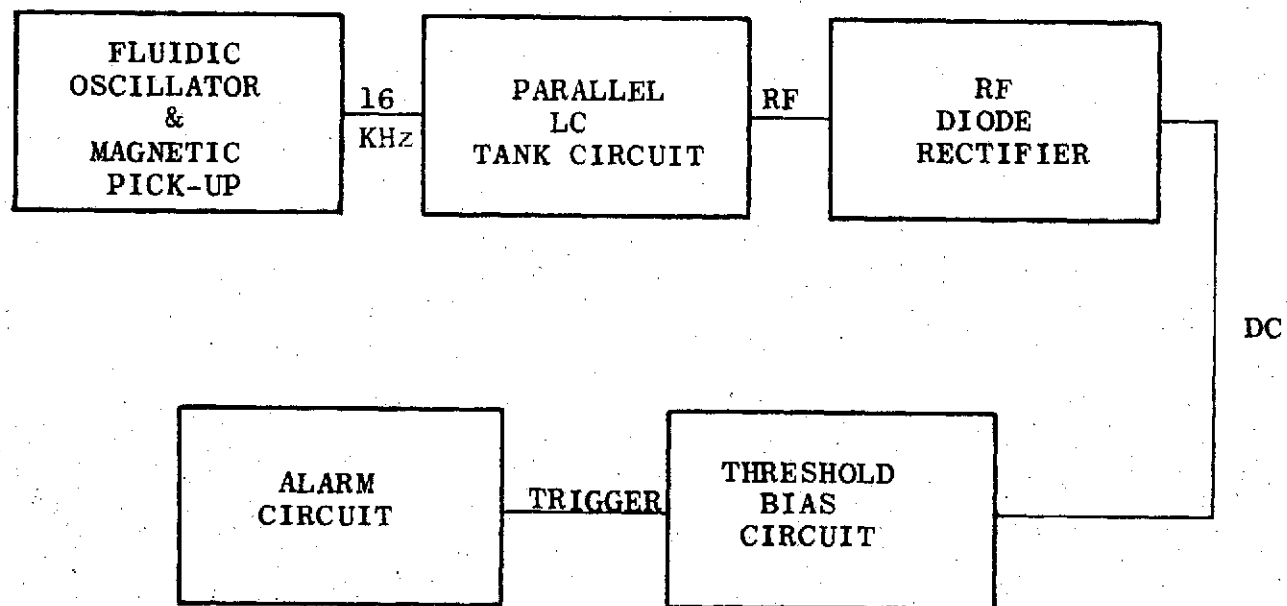


Fig. 59 Fluidic Threshold Detector

Continuous Fluidic Detector. Whereas the previously described detector circuit furnishes an output only above preset threshold level, the detector now under discussion will monitor the hydrogen level continuously, providing an output reading at all times.

In principle the electronic circuit is simple. The 16,000 Hz signal from the magnetic or crystal pick-up is sent to a FM discriminator whose output is directly proportional to the amount of hydrogen in the mixture.

Since the output signal is a rising DC voltage, such an output signal therefore can be read directly across a volt meter which is calibrated in percent of hydrogen detected.

Fig. 60 shows the schematic circuit diagram of this continuous monitoring fluidic detector.

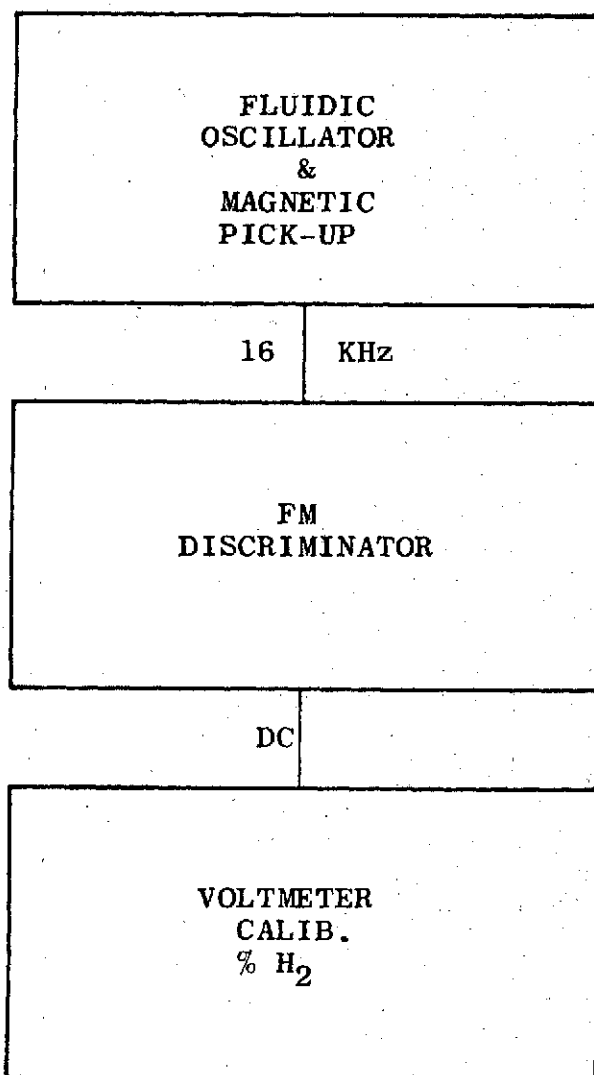


Fig. 60 Continuous Fluidic Detector

OPERATIONAL TESTS AT THE KENNEDY SPACE CENTER

Since under another contract, directed by the principal investigator, large H_2 clouds were produced by mixing of LH_2 and LO_2 , it was decided to take the fluidic gas sensors and investigate their response characteristics under actual field conditions.

During the first of these experiments both the F and the M series were investigated. The oscillators available at that time were able to detect hydrogen concentrations to ± 50 ppm.

The tests were a true field operation. The only source supply, to operate the fluidic gas sensors from, was a garden hose which necessitated the use of a water ejector which was supplying the vacuum needed to operate the "sniffers".

The pressure pulsations from the fluidic oscillator were transformed by a simple transistor radio earphone (transducer) into an electrical signal which was then transmitted through a 400 ft. cable to the test control area where the signal was fed into a tape recorder. The recorder had a loudspeaker so that the sensor operation could be monitored. The sensor itself was mounted about 20 feet from the auto-ignition test stand and downwind from it. The higher oscillator frequency was 12,200 Hz.

During the test the oscillator was frequently observed to be covered by the H_2 cloud or immersed in the lower portion of the cloud. Each time at the time of immersion, the signal was heard to rapidly rise to inaudibility over the speaker system of the recorder.

The recordings made on cassetts which were later processed at the University, by using a frequency to DC converter and thus having a DC signal output proportional to the frequency. A typical run is shown in Fig. 61. The peaks shown correspond with the pattern observed at the

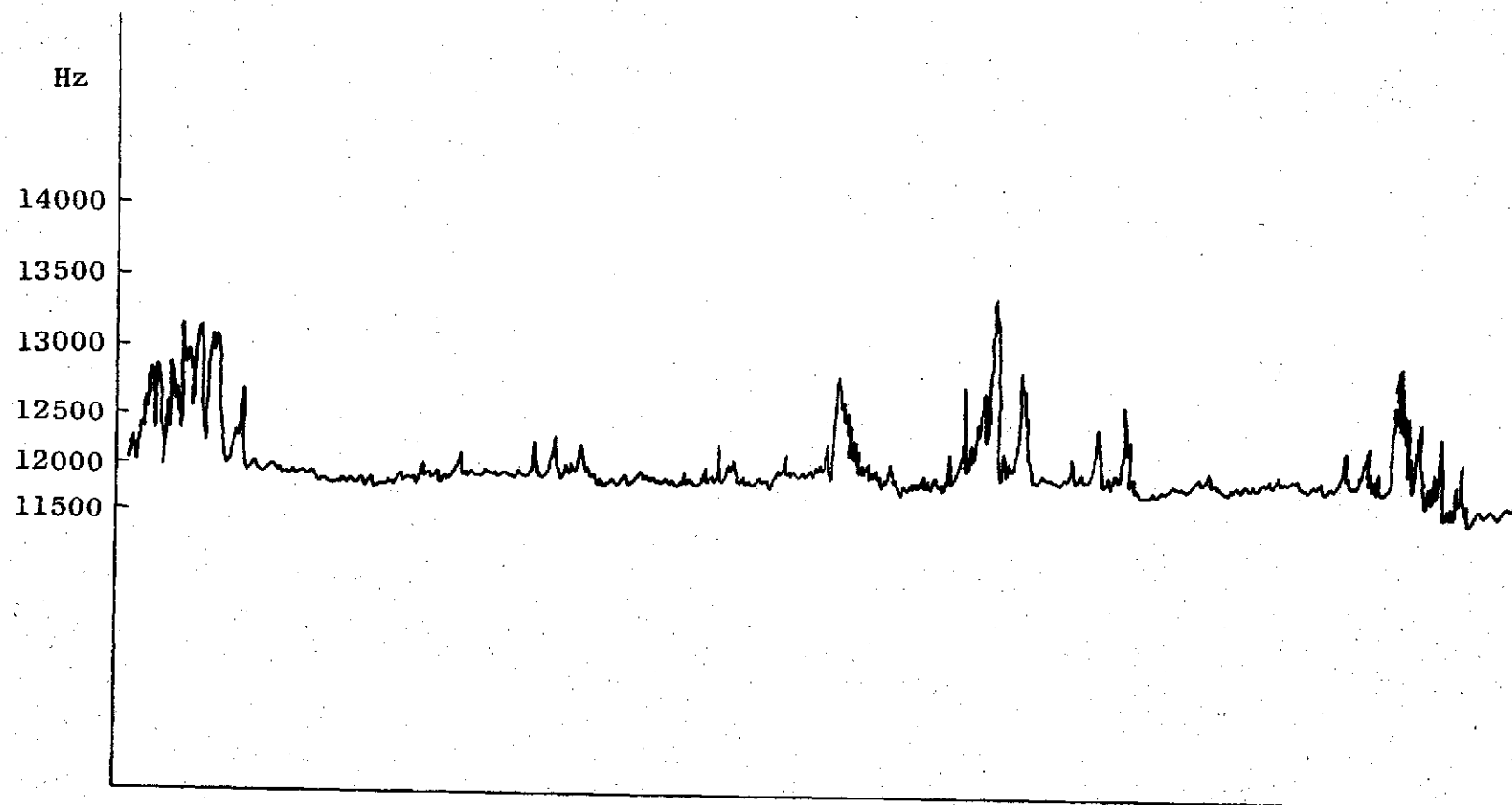


Fig. 61 KSC H₂ Cloud Monitoring Results (Auto-Ignition)

site. Calculations indicate that a maximum of 2.5 percent hydrogen was intercepted by the fluidic sensor. This low concentration was due to the buoyancy of the hydrogen and the rather far location of the sensor. It was observed that most of the time the hydrogen cloud was moving away above the sensor and the higher concentrations were actually present at the top of the cloud.

The tests clearly showed that the fluidic oscillators, the gas sensors, had a very rapid response and very quick recovery rate to the presence of hydrogen.

The above tests were conducted in coordination with the auto-ignition experiments using 6 and 60 pounds of propellants.

By the time the auto-ignition experiments proceeded to the 240 lb. quantities high frequency stable feedback gas sensors were developed and they were then used during the boil-off experiments again tied in with the auto-ignition experiments.

The high frequency oscillators operating above 16,000 Hz were again operated from a water ejector which provided the vacuum and then the signal preamplified was fed through a 1000 ft cable to an oscilloscope to monitor the actual operation of the device and then to a tape recorder which could record up to about 30,000 Hz. The sensor was moved much closer into the cloud only a few feet from the test equipment and the sensor was in the thick cloud of hydrogen vapor. During the first day the concentration was so high in rainy weather that the cold cloud actually froze the rain and after a while froze up the oscillator at the very high concentration of above 50% hydrogen vapor. When the concentration decreased and the temperature rose again the oscillator unfroze and performed perfectly not being bothered by the rain.

The next day a thermocouple was provided to monitor the actual temperature of the hydrogen cloud and it dipped at times below -200 F.

All the data was taken with the S type oscillator which has the feedback loops internally arranged and cut out of the plastic module.

The predicted performance is shown in Fig. 62. This figure gives the pressure changes, the temperature changes, the actual frequency as a function of concentration of hydrogen. Because of the cooling effect of the hydrogen cloud so close to its source of generation the frequency of the fluidic device first increases with concentration and then decreases. Actually this temperature is a double check on the operation of the oscillator since the heat balance so close to the origin of the cloud gives very good concentration results.

Some interference with all the other equipment including fluctuations of the water pressure were observed but all these effects could be filtered out by electronic signal conditioning. Fig. 63 shows again the results from the boil-off experiments with the S series oscillators.

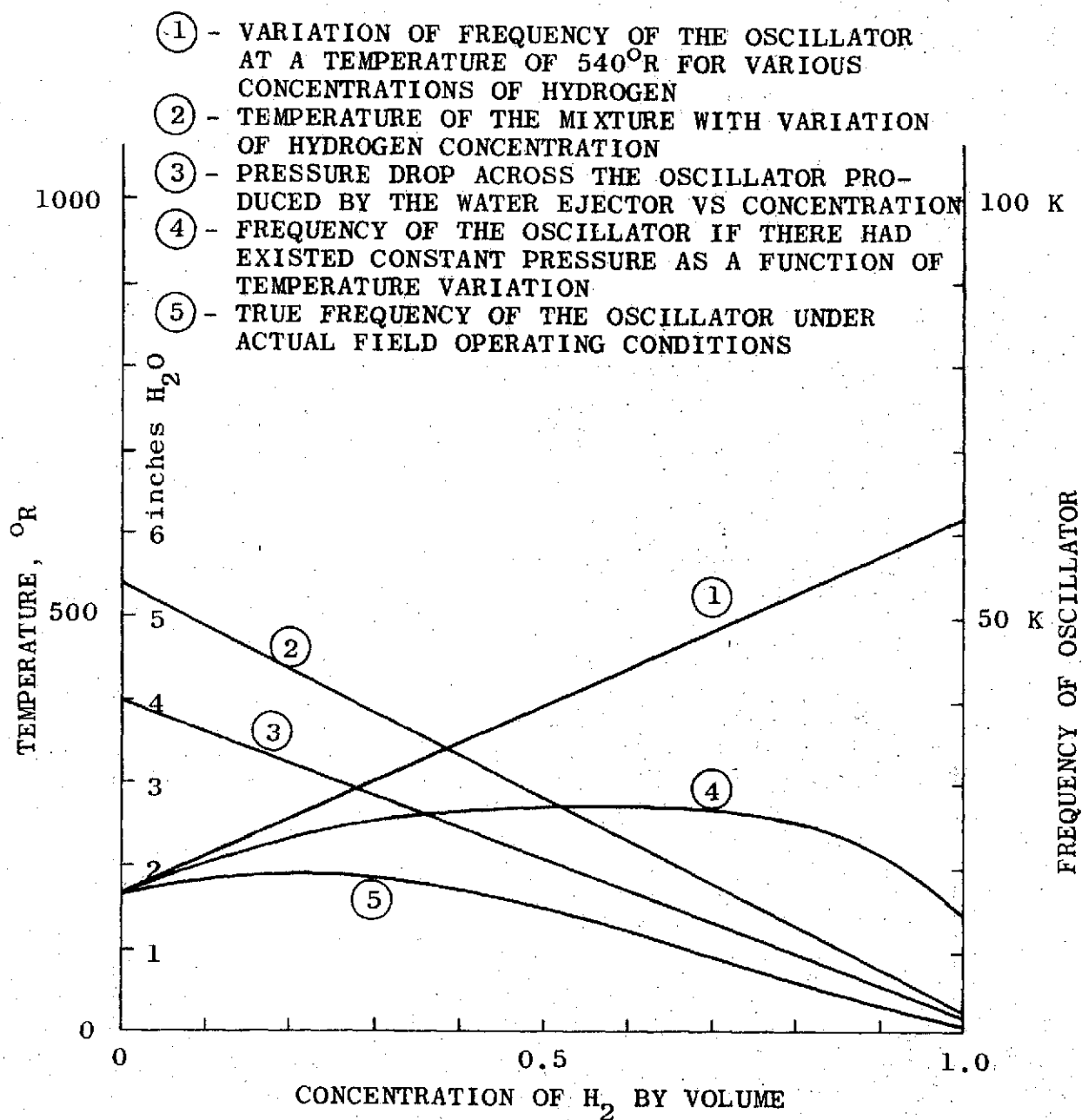


Fig. 62 Theoretical Cloud Monitoring Performance Curves

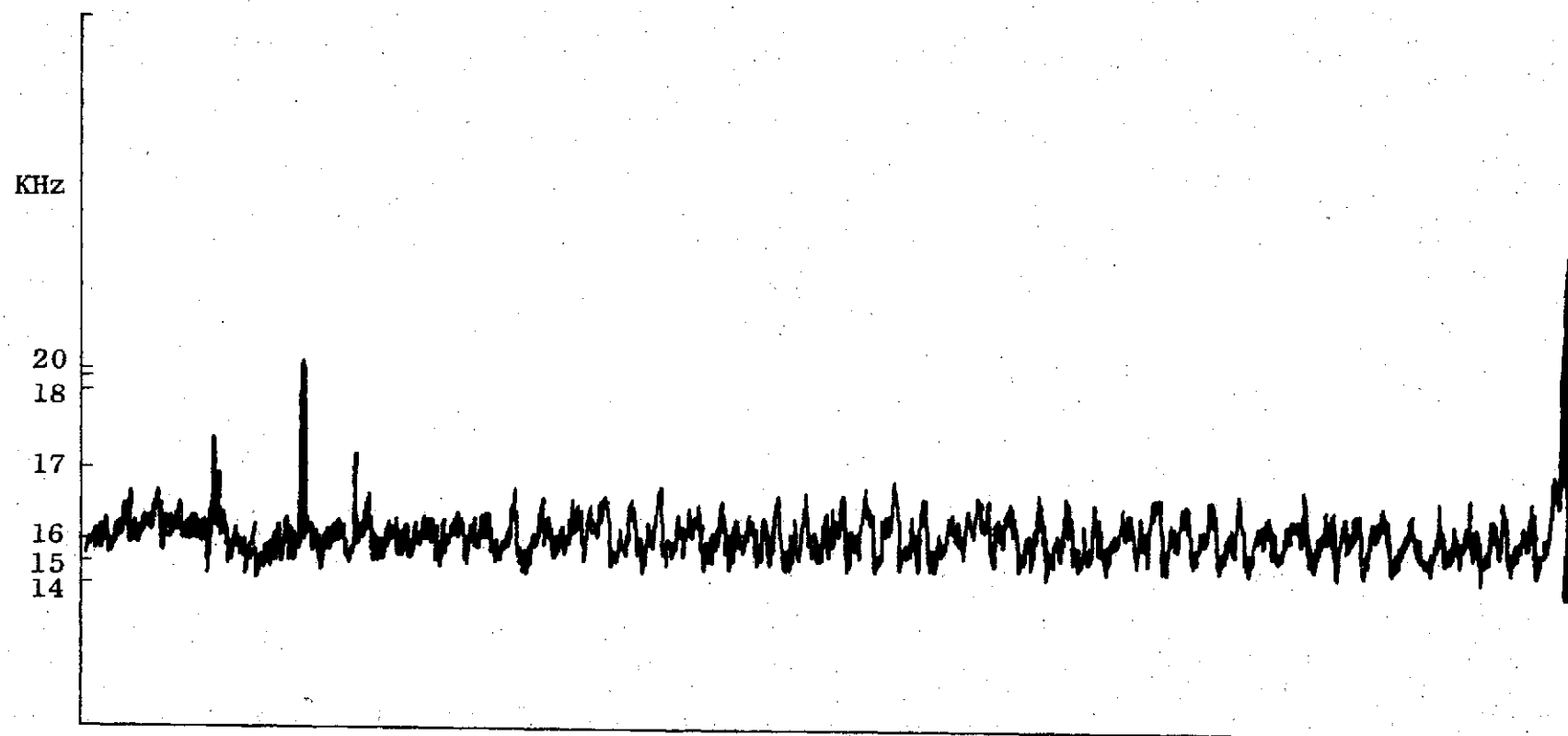


Fig. 63 KSC H₂ Cloud Monitoring Results (LH₂ Boil-off)

DISCUSSION AND EVALUATION

General

The general characteristics of the fluidic oscillators used as gas sensors have been described in detail above giving their actual performance data. In this section the performance will be evaluated on an objective basis and the various questions discussed which are part of the contract evaluation requirements and part of our own operation criteria.

The original idea of using the fluidic oscillator as a gas sensor was proposed because the conventional techniques had very serious shortcomings some of them not allowing them to meet the operational requirements. Probably the most important feature of the fluidic oscillator is that it can sense the gas concentration instantaneously. Other reliable means of determining the gas concentrations depend upon sampling methods which because of the nature of their operation require time.

Furthermore the gas sensor of the fluidic oscillator type is simple, can be designed and mass produced very quickly and inexpensively, it is small, light and reliable, self repairing or healing and has been shown to meet the operational requirement desired here.

Two types of sensor have been developed, the feedback type and the edgetone type. More control can be applied to the feedback type and it, for this reason, looks more promising. It can be designed to have certain characteristics, to go so far as negative pressure and temperature coefficients.

It is possible to use almost any source of supply power, such as electricity, high pressure air or gas lines, high pressure steam lines, low pressure air, gas or steam lines, water lines, etc. By using

ejectors the vacuum needed for the fluidic oscillator to be used as a sniffer can be provided and the whole unit can be potted to be a small box which only has to be connected to the power source. Fig. 64.

It should be said that the objective of this contract was to develop a sensor and not a system. Before the applicability of the sensor is evaluated in an integrated system this system must carefully be analyzed mostly from an economic point of view.

Performance Characteristics and Control

It was seen from the earlier data and discussion that the oscillators can be designed to give high frequency of oscillations or low frequencies. The lower frequencies usually give a higher signal amplitude in the transducer and so it may under certain conditions be advantageous to electronically either multiply the frequency or have the electronic system work on fractional cycle sensitivity to give the ± 50 parts per million desired.

The oscillators used here could go down to about ± 30 ppm and it was shown that cutting the size of the S type feedback oscillator in half doubled its oscillation frequency. The fluidic devices could by proper design, although more work is needed in this area, be made insensitive to pressure or temperature or both. The easiest method to do this was with the F series oscillators which had external feedback loops which could be changed and resistances, capacitances and inductances all of the variable type inserted. By such methods it is believed almost all desired characteristics can be given to an oscillator within certain operating requirements.

Detailed Discussion

The fluidic oscillator as a gas sensor is a very simple device which can be made very broad in its operating

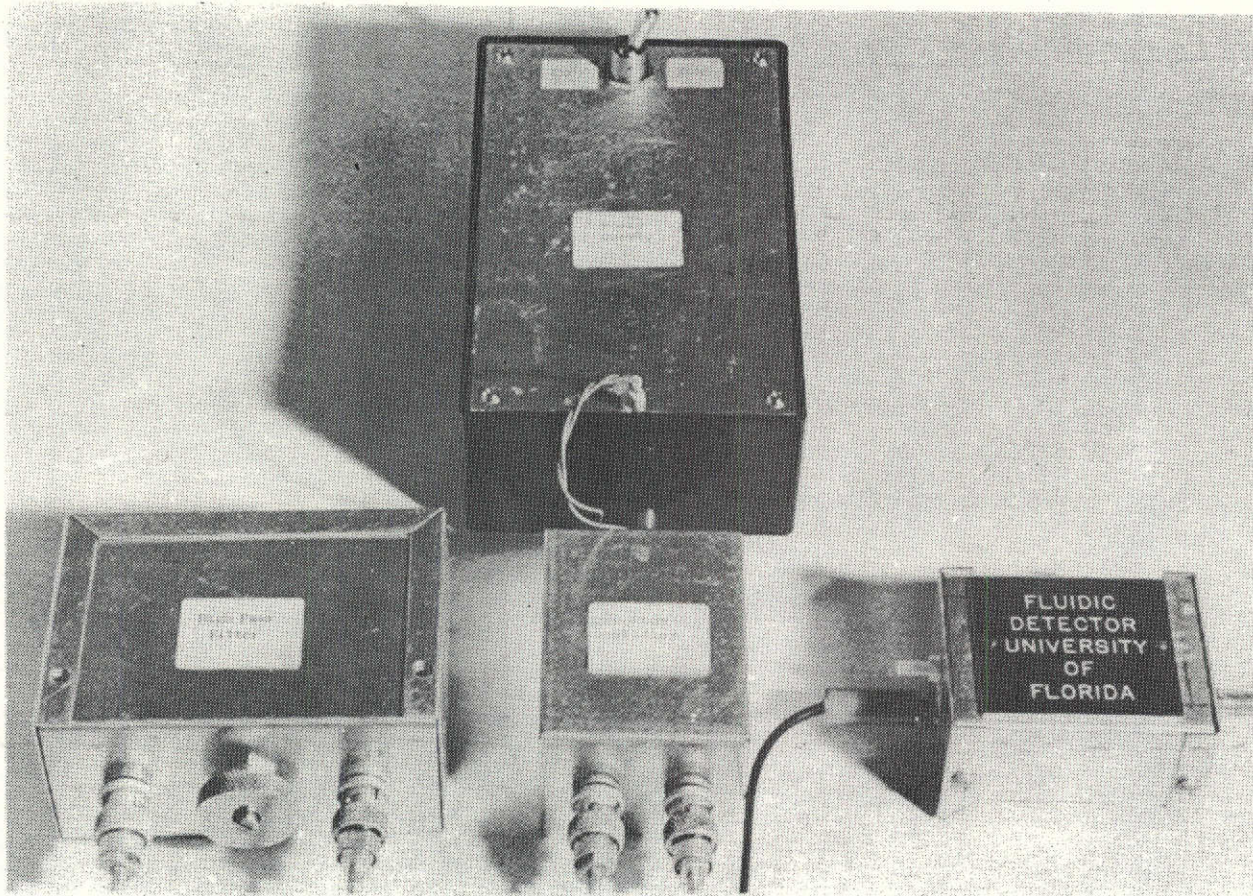


Fig. 64 Potted Gas Sensor

characteristics. Some of the F type oscillators can operate on water at about 30 Hz and up and on air at several hundred or thousand Hz and even with H_2 up to about 20,000 Hz. All this the same oscillator without modifications.

Most of the oscillators built had a much closer range and were designed for a specific purpose. They can be considered a new type hydrogen sensor with an accuracy as high as desired. Some of the oscillators used, not on this project but on others, in our laboratory operated at about and above 200,000 Hz. At these high frequencies the accuracy and sensitivity are greatly improved but the transducer and recorder system increase in cost and complexity manifold.

The fluidic oscillators used in this work had a base frequency in air just above 16,000 Hz giving almost four times that frequency with pure H_2 .

These sensors have an instantaneous sensing capability and recovery rate of the same order. At 16,000 Hz the oscillation frequency of the device could be held within one cycle.

The fluidic devices could be designed so as to be almost independent of pressure and temperature although more work is needed to eliminate the empiricism from the design. The oscillators proved to be linear in response to concentrations of gases.

They could be made to respond to a desired gas like H_2 by using two oscillators and a filter which partially absorbed the gas. Since the device is essentially passive it cannot provide a source of ignition.

It is easily maintained and has proved in field tests to have self healing characteristics it is reliable and light in weight and simple. Mass production from metal or plastic, once the basic unit has been

developed, should be very inexpensive and fast.

The pressure pulses from the unit can be changed into electrical signals by very inexpensive (transistor earphone) transducers to provide display on an oscilloscope, a signal for recording on tape, to power a meter for simple readout or it can be integrated into a warning system.

Depending upon the power source available to drive these fluidic devices they are very flexible with simple auxiliary equipment. Probably the simplest is the ejector type which can provide the needed vacuum from a liquid or gas pressure source usually available. Naturally, pumps, large reservoirs under pressure or boiling off vapors can be used.

From the above discussion it can be seen that the fluidic gas sensor is a simple, reliable device which can be designed to meet desired characteristics and requirements and can do so inexpensively and with safety.

Certain criteria were laid down at the outset of this project and they have been met and demonstrated. The systems have done the task they were required to do and showed their reliability but have not at this time been optimized nor integrated into a whole surveillance system.

The electrical system to utilize and display the signal provided by the transducer coupled to the fluidic oscillator was discussed above. It really was not part of this investigation as such but had to be developed to display and analyze the output from the gas sensors.

The signal amplification and conditioning, however, can be done many different ways and even though we, in many cases, designed our own circuits to save time and cut costs much of commercial equipment available could have been used.

It is believed that this investigation as reported here has made a significant contribution to the gas sensor technology and has provided the basis for new systems with capabilities heretofore unavailable.

CONCLUSIONS

Based upon the work carried out under this contract the following conclusions can be drawn:

1. The Fluidic Oscillator can be used as a gas sensor giving both the sensitivity and stability as well as flexibility required.
2. Both types the feed-back and the edgetone fluidic oscillators can sense H_2 with an accuracy of better than ± 50 ppm.
3. The sensors can be made to respond to the gas desired and with two oscillators and an H_2 absorption filter can distinguish between H_2 and He.
4. The accuracy and reproductibility of the fluidic oscillator was shown to be within one cycle at 16,000 Hz even with a water ejector as the driving power.
5. The response of the fluidic oscillator is instantaneous probably one of the greatest advantages of the device, as well as instantaneous in recovery.
6. The effects of temperature, pressure, wind, rain, etc. can be taken care of by proper design, and the device becomes rather insensitive to environmental conditions.
7. The fluidic oscillator is linear in response to gas concentrations which makes calibration much easier.
8. Since the fluidic device is essentially passive it cannot provide a source of ignition in case it is to be used as gas sensor in explosive mixtures.
9. The fluidic gas sensor not having any moving parts is very reliable and has self-healing qualities when such things as rain drops or dust particles enter the device. Only for an instance will the effects be felt.

10. Simple transistor radio earphones can be used as transducers changing the pressure pulses into electrical signals which can be displayed on oscilloscopes, recorded, or used for meter read-out.
11. The output signal can easily be integrated into a warning system by using a threshold voltage corresponding to a certain critical concentration triggering the system.
12. The size and the weight of the unit are very small and the sources from which the devices can be operated are quite flexible such as a vacuum line, high and low pressure steam and gas lines, water lines, small rotary or vibrator pumps, etc.
13. The sensors can be designed for the ranges required and the electronic system made to give the desired output. The frequencies can be increased in the device or by electronic multiplication to give the desired read-out.
14. The cost of the sensor itself should be very small when mass produced. When a system is considered to be used for a particular application the system cost must be considered which was, however, not part of this investigation.
15. The operational characteristics as described in the main body of the report can be controlled by the design and auxiliary equipment. Introducing resistances, capacitances and inductances into the feedback loops allows designs which make the gas sensor insensitive to pressure and temperature changes.
16. The sensors seemed to be maintenance free and safe as well as reliable in operation as was demonstrated when H_2 clouds were monitored in the field during the auto-ignition experiments at Kennedy Space Center.

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